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An Experimental Evaluation of 26 Light Vehicles Using Test Maneuvers That May Induce On-Road, Untripped Rollover and a Discussion of NHTSA's Refined Test Procedures

Phases VI and VII of NHTSA's Light Vehicle Rollover Research Program

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16. Abstract

The National Highway Traffic Safety Administration (NHTSA) has been researching the area of light vehicle dynamic rollover resistance for nearly thirty years. In the past, repeatability, performability, and discriminatory capability issues compromised maneuvers that endeavored to assess rollover resistance. It was not until recently that NHTSA was able to isolate maneuvers capable of resolving such issues. This report discusses Phases VI and VII of NHTSA's 2001-2002 Light Vehicle Rollover Research Program.

Phase VI was intended to be a comprehensive evaluation of many vehicles, using maneuvers and procedures developed during Phases IV and V. In Phase VI, performed during the spring through fall of 2002, the rollover resistances of a broad range of 26 light vehicles were assessed. The test vehicles were evaluated with one Characterization maneuver and two Rollover Resistance maneuvers, with up to two load configurations per vehicle. The Phase VI vehicle fleet was comprised of nine sport utility vehicles (SUVs), six pick-ups, five minivans, and six passenger cars, selected by vehicle classification, known single-vehicle rollover accident data, and static stability factor (SSF). A detailed description of the testing and results is presented. For the Rollover Resistance maneuvers, two-wheel lift is summarized and its repeatability discussed. Of the 26 vehicles tested, ten produced two-wheel lift.

Phase VII was intended to improve and revise the maneuvers and procedures used in Phase VI. In Phase VII, a "Multi-Passenger" load configuration was defined (a revised version of the Maximum Occupancy configuration used in Phase VI), a means of reporting the occurrence of rim-to-pavement contact and/or debeading was discussed, and the concept of adjusting handwheel angles via scalars to improve rollover resistance maneuver severity was explored. The Multi-Passenger configuration used up to three water dummies placed in rear seating positions. This differed from the Maximum Occupancy configuration in that not in every rear seating position was occupied. Phase VII results indicate the Multi-Passenger loading may be less severe than the Maximum Occupancy configuration for some vehicles, but its use will retain NHTSA's ability to evaluate the rollover resistance of vehicles at two severity levels with higher face validity. Phase VII results indicate steering scalar reductions can improve maneuver severity in cases where steering inputs are so large they saturated the vehicles' tires; the authors recommend revising the test procedure of each maneuver to reflect the reduction of the steering scalars. The authors recommend that a test series be terminated if rim-to-pavement contact is observed, and that this information be included as a supplement to the vehicle's NCAP Rollover Rating.

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Approximate Conversions to Metric Measures					Approximate Conversions to English Measures				
Symbol	When You Know	Multiply by	To Find	Symbol	Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH					LENGTH		
in	inches	25.4	millimeters	mm	mm	millimeters	0.04	inches	in
in	inches	2.54	centimeters	cm	cm	centimeters	0.39	inches	in
ft	feet	30.48	centimeters	cm	m	meters	3.3	feet	ft
mi	miles	1.61	kilometers	km	km	kilometers	0.62	miles	mi
		AREA					AREA		
in^2	square inches	6.45	square centimeters	cm^2	cm^2	square centimeters	0.16	square inches	in^2
ft^2	square feet	0.09	square meters	m^2	m^2	square meters	10.76	square feet	ft^2
mi^2	square miles	2.59	square kilometers	km^2	km^2	square kilometers	0.39	square miles	mi^2
		MASS (weight)					MASS (weight)		
oz	ounces	28.35	grams	g	g	grams	0.035	ounces	oz
lb	pounds	0.45	kilograms	kg	kg	kilograms	2.2	pounds	lb
		PRESSURE					PRESSURE		
psi	pounds per $inch^2$	0.07	bar	bar	bar	bar	14.50	pounds per $inch^2$	psi
psi	pounds per $inch^2$	6.89	kilopascals	kPa	kPa	kilopascals	0.145	pounds per $inch^2$	psi
		VELOCITY					VELOCITY		
mph	miles per hour	1.61	kilometers per hour	km/h	km/h	kilometers per hour	0.62	miles per hour	mph
		ACCELERATION					ACCELERATION		
ft/s^2	feet per $second^2$	0.30	meters per $second^2$	m/s^2	m/s^2	meters per $second^2$	3.28	feet per $second^2$	ft/s^2
		TEMPERATURE (exact)					TEMPERATURE (exact)		
°F	Fahrenheit	5/9 (Celsius) - 32°C	Celsius	°C	°C	Celsius	9/5 (Celsius) + 32°F	Fahrenheit	°F

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For the convenience of visually impaired readers of this report using text-to-speech software, additional descriptive text has been provided for graphical images contained in this report to satisfy Section 508 of the Americans With Disabilities Act (ADA).

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ACKNOWLEDGMENTS

The research documented in this report was a coordinated effort by the National Highway Traffic Safety Administration's (NHTSA) Vehicle Research and Test Center (VTRC) and the Transportation Research Center Inc. (TRC) to experimentally determine the rollover resistance of a broad range of light vehicles. Results from this testing will be used in the development of a dynamic rollover resistance rating system to be used in a consumer information program, as required by the TREAD Act.

The authors wish to recognize the outstanding support of our research colleagues. W. Riley Garrott and Pat Boyd contributed to the development and revision of the test procedures used in this study. Mark Heitz served as an experimenter for many of the tests. Larry Jolliff performed the required driving. Greg Stevens, Jim Preston, Michael Brown, Ian Robbins, Ashley Franz, Edward Hillstrom, and Nicklas Buckner prepared the vehicles for testing by installing instrumentation and outriggers, and assisted with the many necessary tire changes. Dave Dashner and Leslie Portwood performed post-processing of the test and video data. Jan Cooper provided administrative support.

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Devin Elsasser

EXECUTIVE SUMMARY

Introduction

The National Highway Traffic Safety Administration (NHTSA) has been researching the area of light vehicle dynamic rollover propensity for nearly thirty years. In the past, repeatability, performability, and discriminatory capability issues compromised maneuvers that endeavored to assess rollover resistance. It was not until recently that NHTSA was able to isolate maneuvers capable of resolving such issues [1].

Phase VI of NHTSA's 2001-02 Light Vehicle Rollover Research Program used two of these maneuvers to evaluate the rollover resistance of twenty-six light vehicles. Unlike other phases of the Rollover Research Program, Phase VI was not intended to function as a maneuver development tool, but rather to be a comprehensive evaluation of many *vehicles*. Although Phase VI testing included maneuvers used to quantify rollover resistance and handling, only results relating to dynamic rollover propensity are discussed in this report. Phase VI handling test results will be the subject of a future NHTSA Technical Report.

The substantial number of diverse test vehicles used in Phase VI allowed NHTSA to realize maneuver severity may be better optimized if some minor adjustments to the test procedures were implemented. For this reason, Phase VII of NHTSA's Light Vehicle Rollover Research Program was conducted. Phase VII efforts include the definition and evaluation of a Multi-Passenger load configuration, a discussion of issues pertaining to rim-to-pavement contact and/or tire debeading, and an introduction of the concept of adjusting handwheel angles via scalars to improve rollover resistance maneuver severity.

The research described in this report has been performed as part of NHTSA's effort to fulfill the requirements of Section 12 of the "Transportation Recall, Enhancement, Accountability and Documentation (TREAD) Act of November 2000." In this legislation, Congress directed NHTSA to "develop a dynamic test on rollovers by motor vehicles for a consumer information program; and carry out a program conducting such tests." This dynamic rollover resistance rating test is to be incorporated into the New Car Assessment Program (NCAP).

Objective

Phase VI testing was performed during the spring through fall of 2002. The objective of the research was to assess the rollover resistance of a broad range of 26 light vehicles. This was experimentally determined using maneuvers and procedures developed during Phases IV and V of the Light Vehicle Rollover Research Program. The test vehicles were evaluated with one Characterization maneuver and two Rollover Resistance maneuvers. Up to two load configurations per vehicle were used.

The objective of Phase VII was to resolve issues that became apparent during Phase VI rollover resistance testing. Using the Phase VI maneuvers and procedures pertaining to the evaluation of rollover resistance, five vehicles were tested. Up to two load configurations per vehicle were used in Phase VII.

Test Conditions

The Phase VI vehicle fleet was comprised of nine sport utility vehicles (SUVs), six pick-ups, five minivans, and six passenger cars. The vehicles were selected on the basis of vehicle classification, known single-vehicle rollover crash data, and static stability factor (SSF). Most of the vehicles were previously owned and some had been previously used by NHTSA in other programs. Three vehicles were new. So as to minimize any confounding effect worn or damaged suspension components could have on the test results, the suspensions of most used vehicles were refurbished. This work was performed by authorized dealerships to ensure only OEM replacement parts were used. In some cases, inspections performed by the dealers revealed that additional components required replacement (e.g., tie rods, bushings, brake components, etc.). Once all items were replaced, a four-wheel alignment was performed. All alignment settings were within specifications established by the vehicle manufacturers.

Each test vehicle was tested in two configurations: Nominal Load and Maximum Occupancy. The Nominal Load configuration consisted of the driver, instrumentation, and titanium outriggers. In addition to the equipment used in the Nominal Load configuration, Maximum Occupancy loading used water dummies positioned at each seating position for which an adult passenger may be restrained with a seatbelt, with some exceptions. Water dummies were not installed at any front seat position. This not only included the passenger-side front seat, but the middle seat if the vehicle was equipped with a bench seat.

Six of the Phase VI test vehicles were pickups capable of seating only front seat occupants. Since no Maximum Occupancy condition existed for these vehicles, an alternative condition was created. The alternative to Maximum Occupancy loading was used in an attempt to impose a rollover resistance test condition of approximately equal severity to that imposed by the "conventional" Maximum Occupancy condition on a dimensionally similar sport utility vehicle.

When completely filled, a water dummy weighs approximately 175 lbs. For some vehicles, use of completely filled water dummies in every designated seating position caused the front and/or rear Gross Axle Weight Rating (GAWR) and/or Gross Vehicle Weight Rating (GVWR) to be exceeded. This situation required the use of partially filled water dummies. "Partially full" water dummies weighed approximately 108 lbs, a weight similar to that of a 5th percentile female HYBRID III dummy. To prevent "slosh" from confounding test outcome, sections of low density Styrofoam were used to uniformly displace the water.

For Phase VII, the vehicle fleet was comprised of a 2001 Ford Explorer Sport 4x2, two 1997 Ford Rangers (one 4x2, one 4x4), a 1995 Chevrolet Astro, and a 1993 Ford Aerostar. Each vehicle was previously used for Phase VI testing. None of the suspension components were modified or replaced between completion of Phase VI and the beginning of Phase VII.

Each vehicle was tested in the Nominal Load configuration that represents two occupants. The Chevrolet Astro and Ford Aerostar were also evaluated with a "Multi-Passenger" configuration that represents five occupants. In addition to the equipment used in the Nominal Load configuration, Multi-Passenger tests used three full water dummies positioned in the second (Astro) or second and third (Aerostar) seating rows. In the case of the Astro, the second seating row included three seating designated positions. In the case of the Ford Aerostar, the second-row was only designed for two passengers; therefore only two water dummies were positioned in the second row. The third dummy was placed in the center of the third seating row. Water dummies were not installed in any front seat position.

The use of three water dummies allowed NHTSA to investigate how the use of a "standard" (i.e., three water dummies, regardless of seating capacity[1]) five-occupant loading condition may change J-Turn and Road Edge Recovery test outcome from that observed with the "Maximum Occupancy" configuration used in Phase VI.

All Phase VI and VII tests were performed on the Transportation Research Center Inc. (TRC) Vehicle Dynamics Area (VDA) located in East Liberty, Ohio. The test surface was paved with an asphalt mix representative of that used on many Ohio highways. All Phase VI and VII tests were performed on dry pavement.

Test Maneuvers

For both Phase VI and VII, each test vehicle was evaluated with one Characterization maneuver (the Slowly Increasing Steer maneuver) and two Rollover Resistance maneuvers (the NHTSA J-Turn and NHTSA Road Edge Recovery). Slowly Increasing Steer test results were used to define J-Turn and Road Edge Recovery handwheel input magnitudes. Previous NHTSA testing has proven that the Rollover Resistance maneuvers used in this study are capable of inducing on-road, untripped rollover for vehicles with a propensity to rollover. A programmable steering machine was used to generate the handwheel steering inputs for each of the three tests used in this study. Note that the Road Edge Recovery maneuver is equivalent to the NHTSA Roll Rate Feedback Fishhook used in previous rollover research, and differs only in name.

Conclusions

Of the twenty-six vehicles evaluated in Phase VI, ten produced two-wheel lift. The only vehicle for which two-wheel lift was observed during each of the four Rollover Resistance Maneuver and load configuration combinations was the Acura SLX.

The most common tip-up scenario (for five of the ten vehicles; the Honda CR-V, Chevrolet Blazer, Mitsubishi Montero, Ford Ranger 4x4, and Ford Aerostar) was lift during the Maximum Occupancy J-Turn, Nominal Load Road Edge Recovery, and Maximum Occupancy Road Edge Recovery maneuvers.

Three vehicles – the Chevrolet Tracker, the Ford Explorer XLS, and the Toyota 4Runner – only experienced two-wheel lift during Road Edge Recovery tests performed in the Maximum Occupancy configuration.

The Chevrolet Astro was the only vehicle that experienced two-wheel lift during J-Turn and Road Edge Recovery tests performed in the Maximum Occupancy configuration only (i.e., no tip up occurred during tests performed with Nominal Load).

[1] NHTSA's improved water dummy specification criteria is defined in Chapter 9.

The substantial number of diverse test vehicles used in Phase VI allowed NHTSA to realize maneuver severity may be better optimized if some minor adjustments to the test procedure were implemented. For this reason, Phase VII of NHTSA's Light Vehicle Rollover Research Program was conducted. Items addressed in this phase included an improved loading condition (the Multi-Passenger configuration) to take the place of the Maximum Occupancy load configuration, a recommendation of how best to report the occurrence of rim-to-pavement contact and/or debeading in the consumer information program, and an evaluation of the concept of reducing handwheel scalars to improve Rollover Resistance Maneuver severity.

Phase VII testing showed that the Multi-Passenger configuration degraded the rollover resistances of the Astro and Aerostar from that observed during Nominal Load tests. Therefore, use of the Nominal and Multi-Passenger configurations will allow NHTSA to effectively evaluate the rollover resistance of vehicles at two severity levels.

The face validity of the Multi-Passenger loading surpasses that of the Phase VI Maximum Occupancy configuration. Most passenger vehicles are not typically loaded to the limit of their seating capacity [3]. While not necessarily "worst-case," Multi-Passenger loading is far more likely to be realized during actual driving on public roadways. The Multi-Passenger "standard" load permits a comparison of the performance of vehicles under identical test conditions while representing a "worst case" load in 95 to 99 percent of actual rollover crashes, depending on vehicle type.

The reduction of steering scalars can improve the effectiveness of NHTSA's Rollover Resistance maneuvers. However, use of steering scalars less than 6.0 during J-Turn testing and 5.5 during Road Edge Recovery testing do not appear to be advantageous.

For each vehicle evaluated in Phase VII, increasing Road Edge Recovery handwheel scalars resulted in a decreased dwell time. In every case, a steering scalar reduction of 1.0 was great enough that there was no overlapping in the ranges of dwell times associated with each scalar. This indicates a reduction of 1.0 is great enough to significantly affect how the vehicle will respond to the respective maneuver. If maximum roll angle is produced prior to completion of the initial steer during a Road Edge Recovery test, Phase VII results indicate a scalar reduction of 1.0 is generally enough to remedy the condition.

The authors recommend that any test series for which rim-to-pavement contact is made be terminated. Such contact does not have to be so severe that the inner tube is ruptured and inflation pressure is lost. If rim-to-pavement contact occurs, the authors believe the event should be reported as supplemental information to that vehicle's NCAP rollover rating.

1.0 INTRODUCTION

Rollovers are the second most dangerous type of crash occurring on our nation's highways. Only head-on collisions kill more Americans each year than do rollover crashes.

According to the 2000 Fatality Analysis Reporting System (FARS), 9,882 people were killed as occupants in light vehicle rollover crashes, including 8,146 killed in single-vehicle rollovers. FARS shows that 53 percent of light vehicle occupant fatalities in single-vehicle crashes involved a rollover event. The proportion differs greatly by vehicle type: 46 percent of passenger car occupant fatalities in single-vehicle crashes involved a rollover event, compared to 63 percent for pickup trucks, 60 percent for vans/minivans, and 78 percent for sport utility vehicles.

This chapter briefly presents background information relevant to how the National Highway Traffic Safety Administration's (NHTSA) recent rollover resistance research relates with the Agency's New Car Assessment Program (NCAP). Specifically, the recent history of the consumer information program and requirements of the Transportation Recall, Enhancement, Accountability and Documentation (TREAD) Act of November 2000 are summarized, and NHTSA's response to the TREAD Act, its 2001- 02 Rollover Research Program, is outlined.

1.1 Scope of this Investigation

NHTSA has been researching the area of light vehicle dynamic rollover propensity for nearly thirty years. In the past, maneuvers that endeavored to assess rollover resistance were compromised with repeatability, performability, and discriminatory capability issues. It was not until recently that NHTSA was able to isolate maneuvers capable of resolving such issues [1]. Phase VI of NHTSA's 2001-02 Light Vehicle Rollover Research Program used two of these maneuvers to evaluate the rollover resistance of twenty-six light vehicles. Unlike other phases of the Rollover Research Program, Phase VI was not intended to function as a maneuver development tool, but rather to be a comprehensive evaluation of many *vehicles*.

The substantial number of diverse test vehicles used in Phase VI allowed NHTSA to realize that maneuver severity may be better optimized if some minor adjustments to the test procedure were implemented. These minor adjustments included: the definition of a new loading condition (Multi-Passenger) to take the place of Phase VI's Maximum Occupancy loading condition, reporting of the occurrence of rim-to-pavement contact and/or tire debeading in the consumer information program, and adjusting handwheel scalars to improve rollover resistance maneuver severity. These adjustments were the subject of Phase VII of NHTSA's Light Vehicle Rollover Research Program, conducted during the winter of 2002/2003 using five vehicles previously evaluated as part of Phase VI.

Tests performed during NHTSA's 2001- 02 Rollover Research Program were not limited to just rollover resistance maneuvers. Since it is possible to achieve high rollover resistance at the expense of poor handling (e.g., by installing "slippery" tires), NHTSA is also very interested in light vehicle handling. As such, an exploration into maneuvers that might be used to assess light vehicle handling was begun in Phase IV, and continued throughout Phase VI. In addition to the two Rollover Resistance Maneuvers used in Phase VI, a suite of Handling Maneuvers was also performed. For the sake of the brevity, as well as the desire to limit the scope of this report to rollover resistance, results from the Phase VI handling tests will be documented in a future NHTSA Technical Report.

1.2 Consumer Information on Rollover Resistance

In a June 1, 2000 Federal Register notice [2], NHTSA proposed to include consumer information star ratings for rollover resistance of passenger cars and light trucks as part of its NCAP. NCAP has provided comparative consumer information on vehicle performance in frontal and side impact crashes for many years. NHTSA proposed a rating system based on the Static Stability Factor (SSF). SSF is the ratio of one half the vehicle's average track width divided by its center of gravity height. SSF was chosen over vehicle maneuver tests because it represents the first order factors that determine vehicle rollover resistance. Other reasons for selecting the SSF measure were: driving maneuver test results are greatly influenced by SSF, the SSF is highly correlated with actual crash statistics, it can be measured accurately and explained to consumers, and changes in vehicle design to improve SSF are unlikely to degrade other safety attributes.

In general, the response of the automotive manufacturers to the June 2000 notice were that star ratings based on SSF were too simplistic because they did not include the effects of suspension deflections, tire traction, and electronic stability control and that the influence of vehicle factors on rollover risk was so slight that vehicles should not be rated for rollover resistance. The Consumers Union commented that although SSF is a useful predictor of tripped rollover, it should be used in conjunction with a dynamic stability test using vehicle maneuvers to better predict the risk of untripped rollovers.

In the fiscal year 2001 Department of Transportation Appropriation Act, Congress allowed NHTSA to move forward with providing consumer information star ratings based on SSF for rollover resistance. However, Congress also directed NHTSA to fund a National Academy of Sciences' (NAS) study on vehicle rollover ratings. The study was to assess "whether the static stability factor is a scientifically valid measurement that presents practical, useful information to the public including a comparison of the static stability factor test versus a test with rollover metrics based on dynamic driving conditions that may induce rollover events." One of the major recommendations from this study was that "NHTSA should vigorously pursue its ongoing research on driving maneuver tests for rollover resistance, mandated under the TREAD Act, with the objective of developing one or more dynamic tests that can be used to assess transient vehicle behavior leading to rollover" [4].

Following the receipt and consideration of comments from interested parties, in a January 12, 2001 notice in the Federal register [5], NHTSA announced that it would proceed with the consumer information star ratings on rollover resistance based on SSF. Rollover resistance star ratings have been added to the frontal and side crash star ratings that were previously provided by the New Car Assessment Program (see www.nhtsa.dot.gov/NCAP/ for ratings, vehicle details and explanatory information).

1.3 Rollover Resistance Requirements of the TREAD Act

Section 12 of the "Transportation Recall, Enhancement, Accountability and Documentation (TREAD) Act of November 2000" directs NHTSA to "develop a dynamic test on rollovers by motor vehicles for a consumer information program; and carry out a program conducting such tests." This dynamic rollover resistance rating test is to be incorporated into the New Car Assessment Program (NCAP). The research presented in this report has been performed as part of NHTSA's effort to fulfill these requirements.

1.4 NHTSA's 2001 - 02 Rollover Research Program

In response to the TREAD Act, NHTSA has performed Phases IV, V, and VI of its Light Vehicle Rollover Research program. These phases are briefly described below:

1.4.1 Phase IV: Maneuver Selection and Procedure Development

Phase IV tests were performed during the spring through fall of 2001. This phase was a comprehensive evaluation of maneuvers that might be used to assess on-road, untripped rollover resistance of light vehicles. Using four sport utility vehicles and three load configurations, five Vehicle Characterization and eight Rollover Resistance maneuvers were studied. The Rollover Resistance maneuvers were evaluated based upon four factors:

- Objectivity and Repeatability
- Performability
- Discriminatory Capability
- Appearance of Reality

For each evaluation factor, each Rollover Resistance maneuver received one of five adjectival ratings (Excellent, Good, Satisfactory, Bad, or Very Bad). Four Phase IV maneuvers received ratings of "Satisfactory" or better. Of these maneuvers, the NHTSA Road Edge Recovery and J-Turn were deemed the most desirable. In the authors' opinion, these maneuvers were adequate for use in a Government rollover resistance rating system.

In addition to the Rollover Resistance maneuvers used in Phase IV, limited handling tests were also performed. Low and moderate severity step-steer maneuvers were used to examine response time. Maximum lateral acceleration and understeer/oversteer behavior at the limit was measured during two different Characterization Maneuvers.

The results of the Phase IV rollover resistance research were released in October 2002. Handling test results will be documented in a future NHTSA Technical Report.

1.4.2 Phase V: Maneuver and Procedure Finalization

Phase V focused on resolving a number of outstanding dynamic rollover testing issues. Using a reduced set of maneuvers (those recommended at the conclusion of Phase IV), the primary objectives of Phase V were twofold:

1. Finalize the test methodology and procedures to be used during Phase VI of the Light Vehicle Research program, including an evaluation of instrumentation developed to measure wheel lift.

2. Investigate how different outrigger designs, ambient temperatures, and test surfaces can affect the outcomes of maneuvers used in a Government rollover resistance rating system.

Testing for this phase was performed during the winter of 2001 through the spring of 2002. The Phase V test results will be documented in a series of future NHTSA Technical Reports.

1.4.3 Phase VI: Fleet Characterization

Phase VI focused on determining the rollover resistance of a substantial number of vehicles. Testing for this phase was performed during the spring through fall of 2002. The objectives of Phase VI of the Light Vehicle Rollover Research Program were:

1. To experimentally determine the rollover resistance of a broad range of light vehicle classes and, within classes, vehicle sizes using the test maneuvers and procedures developed during Phases IV and V of the Light Vehicle Rollover Research Program.

2. Use the results from this testing to assist in the development of a dynamic rollover resistance rating test that can be incorporated into NCAP (as required by the TREAD Act).

The results of Phase VI research are documented in this report.

1.4.4 Phase VII: Refinements of Phase VI Procedures and Maneuvers

During Phase VI testing, several issues were uncovered regarding the test procedures and maneuvers used. Phase VII was conducted to address these issues:

1. Due to inconsistencies in achieving the Maximum Occupancy loading, combined with difficulties in achieving the loading without violating the vehicle's front, rear, and/or vehicle weight ratings, a new loading configuration was developed. This new configuration, referred to as the "Multi-Passenger Configuration," consisted of reducing the number of water dummies from five or six (depending on the vehicle) to three for two minivans used in Phase VI research. Testing was performed to demonstrate how J-Turn and Road Edge Recovery test outcomes might change as a function of the number of water dummies.

2. Due to the severe demands of the J-Turn and Road Edge Recovery maneuvers, rim-to-pavement contact and tire debeading occasionally occur. These events, aside from the damage they may cause to the test facility, may

affect the manner in which the Phase VI Rollover Resistance maneuvers are executed, and in some cases, it is possible that two-wheel lift may not be detected (due to early termination of the test series because of rim-to-pavement contact or tire debeading).

3. During Phase VI testing, it was found that maneuver severity might be better optimized if handwheel angles are either reduced or increased. In some cases, the magnitude of the steering input resulted in a vehicle's tires reaching saturation before the completion of the test maneuver. By reducing the scalars defining handwheel inputs by 1.0 for both NHTSA's J-Turn and Road Edge Recovery tests, maneuver severity can be optimized. For other vehicles, it was found that maximum maneuver severity wasn't achieved due to small handwheel input angles. By increasing the scalars defining handwheel inputs by 1.0, maneuver severity for these vehicles can be optimized.

The results of Phase VII research are documented in this report.

1.5 Structure of This Report

Chapter 1 has briefly presented the rollover safety problem, summarized NHTSA's recent research, and discussed the mandate of the TREAD Act. Chapter 2 explains the objectives and test matrix for the work presented in this report. Chapter 3 describes the test vehicles, discusses the various vehicle configurations used for this research, and discusses the tires and outriggers that were used. Chapter 4 describes the instrumentation and data acquisition systems that were installed in each test vehicle.

Chapter 5 discusses the one Characterization Maneuver (Slowly Increasing Steer), and two Rollover Resistance Maneuvers (NHTSA J-Turn and NHTSA Road Edge Recovery) used in Phases VI and VII. This chapter includes maneuver descriptions and presents the J-Turn and Road Edge Recovery handwheel steering angles used for each vehicle. For the sake of brevity, results from NHTSA's Handling Maneuvers will be discussed in a later report.

Chapter 6 is an assessment of the ability of the steering machine (used for all steering inputs in this study) to achieve the commanded handwheel angles and rates.

Chapter 7 presents NHTSA J-Turn and NHTSA Road Edge Recovery maneuver test results for both Phase VI and Phase VII. The occurrences of two-wheel lift, and the maneuver entrance speeds required to produce it, are presented. Additionally, rim-to-pavement contact and tire debeading discussions are provided.

Chapter 8 describes the test repeatability of the NHTSA J-Turn and NHTSA Road Edge Recovery maneuvers. Since the input repeatability of these maneuvers has been well documented, this chapter focuses on the two-wheel lift repeatability of two tests performed with nearly equivalent maneuver entrance speeds.

Chapter 9 discusses rim-to-pavement contact and tire debeading, along with a clarification of the Multi-Passenger load configuration.

Chapter 10 features the overall conclusions from Phases VI and VII of NHTSA's Light Vehicle Rollover Research Program.

2.0 OBJECTIVES

2.1 Work Performed

Phase VI focused on determining the rollover resistance of a substantial number of vehicles. The objective of this phase was to experimentally determine the rollover resistance of a broad range of light vehicles using the test maneuvers and procedures developed during Phases IV and V of the Light Vehicle Rollover Research Program. Phase VII was conducted to resolve issues raised during Phase VI rollover resistance testing. Twenty-six vehicles were evaluated during Phase VI, and five vehicles were evaluated during Phase VII. Each phase used one Characterization maneuver and two Rollover Resistance maneuvers capable of inducing on-road, untripped rollover.

2.1.1 Vehicles Tested

The Phase VI vehicle fleet was comprised of nine sport utility vehicles (SUVs), six pick-ups, five minivans, and six passenger cars. The vehicles were selected on the basis of vehicle classification, known single-vehicle rollover crash data, and static stability factor (SSF). Most of the vehicles were purchased as used from dealerships in the vicinity of NHTSA's Vehicle Research and Test Center (VRTC) located in East Liberty, Ohio. Others were previously purchased by NHTSA for use in other test programs. Three vehicles were purchased as new for Phase VI. So as to minimize any confounding effect worn or damaged suspension components could have on the test results, the suspensions of the used vehicles were refurbished[2]. This work was performed by authorized dealerships to ensure only OEM replacement parts were used. Table 2.1, presented at the end of Section 2.2, contains a list of the Phase VI test vehicles. Additional information about these test vehicles is contained in Chapter 3 of this report.

The Phase VII vehicle fleet was a subset of the fleet used for Phase VI testing and included a 2001 Ford Explorer Sport 4x2, two 1997 Ford Rangers (one 4x2, one 4x4), a 1995 Chevrolet Astro, and a 1993 Ford Aerostar. The Ford Explorer was one of the three vehicles purchased new for Phase VI testing. None of the suspension components were modified or replaced between completion of Phase VI and the beginning of Phase VII. Table 2.2 contains a list of the Phase VII test vehicles. Additional information about the test vehicles for Phases VI and VII is contained in Chapter 3 of this report.

2.1.2 Load Configurations

Each test vehicle was tested in two load configurations for Phase VI, and a new load configuration was added for Phase VII. Configuration descriptions are as follows:

> **Nominal Load.** The Nominal Load consisted of the driver, instrumentation, a steering machine, and titanium outriggers. Each vehicle was fully fueled.

[2] The suspensions of the 2001 Toyota 4Runner and 2001 Chevrolet Blazer were not refurbished. In the opinion of the authors, replacement of suspension components was not necessary for these vehicles since they were purchased new by NHTSA in 2001 for Phase IV and V rollover research.

Maximum Occupancy (Phase VI). In addition to the equipment used in the Nominal Load configuration, Maximum Occupancy tests generally used water dummies positioned at each seating position for which an adult passenger may be restrained with a seatbelt. Water dummies were not installed at any front seat position. This not only included the passenger-side front seat, but the middle seat if the vehicle was equipped with a bench seat. In Phase VI, six vehicles were pickups capable of seating only front seat occupants. Since no Maximum Occupancy configuration existed for these vehicles, an alternative condition was created. This alternative was used in an attempt to impose a rollover resistance test condition of approximately equal severity to that imposed by the "conventional" Maximum Occupancy configuration on a dimensionally similar sport utility vehicle.

Multi-Passenger Configuration (Phase VII). In addition to the equipment used in the Nominal Load configuration, Multi-Passenger tests used three full water dummies (weighing 175 lbs each) positioned in each second-row seating position for which an adult passenger may be restrained with a seatbelt. If the second-row was only designed for two passengers, only two water dummies were positioned in the second row. The third dummy was then placed in the center of the third seating row. Water dummies were not installed at any front seat position.

2.1.3 Maneuvers Examined

Phases VI and VII used two Rollover Resistance maneuvers: the NHTSA J-Turn and the NHTSA Road Edge Recovery. These maneuvers both require data output from a single Characterization maneuver, the Slowly Increasing Steer. Brief maneuver descriptions are as follows:

Slowly Increasing Steer. This maneuver requires the steering wheel be turned slowly to 270 degrees while the driver attempts to maintain a constant speed. Although Slowly Increasing Steer tests can be used to provide important handling information, NHTSA's Rollover Resistance tests only require data output from the maneuver to define handwheel input magnitudes. For the sake of brevity, this paper does not discuss how the Slowly Increasing Steer maneuver pertains to the assessment of handling. This topic will be addressed in a later report.

NHTSA J-Turn. The Phase VI J-Turn is identical to that used in Phases IV and V. The maximum handwheel steering angle magnitude was equal to 8.0 times the handwheel angle at which 0.3 g lateral acceleration was attained during Slowly Increasing Steer tests performed with the same vehicle and vehicle load configuration. The Phase VII J-Turn is identical to the Phase VI J-Turn, except that the scalar multiplier was increased or decreased so as to maximize the severity of the J-Turn maneuver.

NHTSA Road Edge Recovery. The NHTSA Road Edge Recovery maneuver is identical to the Phase IV Fishhook 1b maneuver (also know as the NHTSA Roll Rate Feedback Fishhook). The maximum handwheel steering angle magnitude was equal to 6.5 times the handwheel angle at which 0.3 g lateral acceleration was attained during Slowly Increasing Steer tests performed with the same vehicle and vehicle load configuration. Like Fishhook 1b, the countersteer magnitude was equivalent to the maximum initial steer, and roll rate feedback is used to determine handwheel reversal timing. The Phase VII Road Edge Recovery maneuver is the same as the Phase VI Road Edge Recovery maneuver, except that the scalar multiplier was increased or decreased so as to maximize the severity of the Road Edge Recovery maneuver.

More complete details of the Slowly Increasing Steer, J-Turn, and Road Edge Recovery maneuvers as used in Phases VI and VII are provided in Chapter 5. Results from the Rollover Resistance maneuvers are provided in Chapters 6, 7, and 8.

2.1.4 Phase VI Test Matrix

Table 2.1 presents the Phase VI rollover resistance maneuver test matrix. The matrix indicates which maneuvers were examined for each vehicle and vehicle configuration. A brief explanation of why some maneuver/vehicle/load combinations were not performed is given after Table 2.1; a more detailed discussion is provided in Chapter 7.

No two-wheel lift was produced during any Maximum Occupancy J-Turn or Road Edge Recovery test performed with the Ford F150 (1992), Chevrolet K1500, or Ford Ranger 4x2. Since the SSFs of these vehicles in the Nominal Load configuration were each greater than those measured at Maximum Occupancy, the tests performed at Maximum Occupancy were considered to be "worst case." The authors do not believe it is possible for increased rollover resistance to coincide with a decrease in SSF (for the same vehicle), therefore the Nominal Load Rollover Resistance tests were deemed unnecessary. In the interest of timesavings, these tests were thus omitted from the Phase VI test matrix.

Two-wheel lift was produced during Nominal Load Road Edge Recovery tests performed with the Ford Ranger 4x4. Since the SSF of this vehicle in the Nominal Load configuration was greater than that measured at Maximum Occupancy, and because authors do not believe it is possible for increased rollover resistance to coincide with a decrease in SSF (for the same vehicle), Maximum Occupancy Road Edge Recovery tests were deemed unnecessary. In the interest of timesavings, these tests were therefore omitted from the Phase VI test matrix.

Due to its lack of designated rear seating positions and its hatchback configuration, it was not possible to evaluate the Chevrolet Corvette in the Maximum Occupancy configuration.

Table 2.1. The Phase VI Test Matrix.

Vehicle	Slowly Increasing Steer		NHTSA J-Turn		NHTSA Road Edge Recovery	
	Nominal Load	Maximum Occupancy	Nominal Load	Maximum Occupancy	Nominal Load	Maximum Occupancy
1998 Honda CR-V	X	X	X	X	X	X
1998 Chevrolet Tracker	X	X	X	X	X	X
1997 Jeep Cherokee Sport	X	X	X	X	X	X
2001 Toyota 4Runner*	X	X	X	X	X	X
1996 Acura SLX	X	X	X	X	X	X
2001 Ford Explorer XLS	X	X	X	X	X	X
2001 Ford Explorer Sport	X	X	X	X	X	X
2001 Chevrolet Blazer	X	X	X	X	X	X
1995 Mitsubishi Montero	X	X	X	X	X	X
1992 Ford F-150	X	X	--	X	--	X
1994 Chevrolet C1500	X	X	X	X	X	X
1997 Ford F-150	X	X	X	X	X	X
1995 Chevrolet K1500	X	X	--	X	--	X
1997 Ford Ranger 4x2	X	X	--	X	--	X
1997 Ford Ranger 4x4	X	X	X	X	X	--
1998 Plymouth Voyager	X	X	X	X	X	X
1995 Ford Windstar GL	X	X	X	X	X	X
1994 Dodge Caravan	X	X	X	X	X	X
1995 Chevrolet Astro	X	X	X	X	X	X
1993 Ford Aerostar	X	X	X	X	X	X
2002 Chevrolet Corvette	X	--	X	--	X	--
1994 Ford Taurus	X	X	X	X	X	X
1993 Chevrolet Caprice Classic	X	X	X	X	X	X
1992 Honda Civic LX	X	X	X	X	X	X
1991 Chevrolet Cavalier	X	X	X	X	X	X
1997 Chevrolet Metro	X	X	X	X	X	X

X = Test was performed
-- = Test not performed

*The electronic stability control (VSC) installed on the model year 2001 4Runner was disabled during all tests performed in Phase VI. Since the only significant difference between model year 2000 and 2001 4Runners is the presence of stability control (not available in 2000, standard equipment in 2001), the performance of the 2001 model with disabled stability control is representative of an otherwise equivalent 2000 model.

2.1.5 Phase VII Test Matrix

Table 2.2 presents the Phase VII rollover resistance maneuver test matrix. The matrix indicates which maneuvers were examined for each vehicle and vehicle configuration.

As shown in Table 2.2, not every vehicle was evaluated with alternative loading and steering scalars. The two Ford Rangers and the Ford Explorer 4x2 were not evaluated in the Multi-Passenger configuration since they were evaluated with only two or three water dummies in Phase VI. Reduced steering scalars were not required for the Ford Explorer 4x2 because the Road Edge Recovery handwheel dwell times were generally greater than or equal to 80 ms in Phase VI[3]. Only the Ford Explorer 4x2 was evaluated with increased steering scalars. Of the nine sport utility vehicles evaluated in Phase VI, the Explorer 4x2 used the smallest steering angles (when evaluated in the Nominal Load configuration). Although no two-wheel lift was produced during Phase VI rollover resistance tests with this vehicle, tip-up was observed during a handling test performed in the Rear Load configuration. To determine whether the small handwheel angles impaired the effectiveness of the J-Turn or Road Edge Recovery, the magnitude of the steering was increased during Phase VII testing.

Table 2.2. Phase VII Test Matrix.

Vehicle	Multi-Passenger Configuration	Reduced Steering Scalar For Improved Severity and Dwell Times*	Increased Steering Scalar For Improved Severity
1995 Chevrolet Astro	Slowly Increasing Steer J-Turn Road Edge Recovery	J-Turn Road Edge Recovery	Test Not Performed
1993 Ford Aerostar	Slowly Increasing Steer J-Turn Road Edge Recovery	J-Turn Road Edge Recovery	Test Not Performed
1997 Ford Ranger 4x2	Test Not Performed	J-Turn Road Edge Recovery	Test Not Performed
1997 Ford Ranger 4x4	Test Not Performed	J-Turn Road Edge Recovery	Test Not Performed
2001 Ford Explorer 4x2	Test Not Performed	N/A	J-Turn Road Edge Recovery

*Improved Dwell Time severity is only applicable for Road Edge Recovery maneuvers.

[3] When the Phase VII vehicles were selected, complete analysis of the Phase VI test data had not yet been completed. At that time, the available Phase VI handwheel data indicated the duration of the steering machine's mechanical overshoot was approximately 80 ms. Later analyses indicated that for some vehicles, the overshoot lasted approximately 120 ms. In hindsight, the Ford Explorer 4x2 (Nominal Load dwell time range: 110-145 ms) should have also been evaluated with reduced handwheel scalars in Phase VII.

2.2 Test Surface

All Phase VI and VII tests were performed on the Transportation Research Center Inc. (TRC) Vehicle Dynamics Area (VDA) located in East Liberty, Ohio. The VDA is an 1800 by 1200 foot flat paved surface with a one percent longitudinal grade for drainage. Turn-around loops are provided on each end to facilitate high speed entry onto the VDA. The surface was paved with an asphalt mix representative of that used on many Ohio highways. All Phase VI and VII tests were performed on dry pavement.

The VDA's peak and sliding coefficients of friction were generally monitored twice per month, weather-permitting, using American Society for Testing and Materials (ASTM) procedures. The peak coefficient was determined with ASTM procedure E1337 and an E1136 tire [6,7]. Sliding coefficients were determined with ASTM procedure E274 and an E501 tire [8,9]. Table 2.3 summarizes the available results for the time period over which Phase VI and Phase VII testing was conducted in 2002-2003.

Phase VI tests were performed from March 3 through November 20, 2002, while Phase VII tests were performed between November 8, 2002 through January 13, 2003. The VDA's peak coefficient of friction ranged from 0.92 to 0.99 during the Phase VI testing period. The slide coefficient varied slightly less, ranging from 0.82 to 0.88. Although peak coefficient of friction measurements of the VDA were limited during the time Phase VII tests were performed, the authors expect it was within the 0.92 to 1.01 range observed from January 3, 2002 to January 9, 2003. The slide coefficients observed during Phase VII were available, however, and ranged from 0.82 to 0.89 during that period. As could be inferred from the test dates, testing was performed with a fairly broad range of ambient temperatures. The lowest ambient testing temperature was approximately 34° F, recorded prior to a series of tests performed on November 18th. The highest ambient testing temperature was approximately 90° F, recorded prior to a series of tests performed on June 25th and August 2nd.

Table 2.3. Peak and Slide Coefficients of Friction During Calendar Years 2002 and 2003 for the TRC VDA.

Date	Coefficient Of Friction	
	Peak	Sliding
01.03.2002	0.95	0.85
03.29.2002	0.96	0.85
04.05.2002	0.92	not available
05.01.2002	0.98	not available
05.30.2002	0.99	0.86
07.05.2002	0.97	0.85
07.23.2002	0.95	0.83
08.14.2002	0.98	0.88
08.29.2002	0.97	0.86
09.19.2002	0.99	0.87
10.08.2002	0.98	0.88
10.22.2002	0.96	0.87
11.04.2002	not available	0.82
11.19.2002	0.98	0.86
12.03.2002	1.01	0.87
01.09.2003	not available	0.89

3.0 TEST VEHICLES AND CONFIGURATIONS

3.1 Vehicle Selection Rationale

The Phase VI vehicle fleet was comprised of nine SUVs, six pick-ups, five minivans, and six passenger cars. The vehicles were selected on the basis of vehicle classification, known single-vehicle rollover crash data, and SSFs. Most of the vehicles were purchased as used from dealerships in the vicinity of NHTSA's VRTC. Others were previously purchased by NHTSA for use in other test programs. Three vehicles were, however, purchased as new for Phase VI: a 2002 Chevrolet Corvette, 2001 Ford Explorer 4x2, and a 2001 Ford Explorer 4x4.

Table 3.1 provides several descriptive parameters for each test vehicle. These parameters are not intended to be comprehensive descriptions of each vehicle, but to highlight certain features the authors deemed relevant to rollover propensity. This table presents *baseline* test weights and SSF-based rollover resistance ratings only. The effects of outrigger installation, instrumentation, etc. are not represented in Table 3.1; rather they are discussed in a later section of this chapter.

So as to minimize any confounding effect worn or damaged suspension components could have on the test results, the suspensions of the used vehicles were refurbished[4]. This work was performed by authorized dealerships to ensure only OEM replacement parts were used (e.g., the Honda Civic and CR-V were serviced at a Honda dealer). At a minimum, the follow items were replaced, regardless of their condition:

1. Front and rear shock absorbers / struts
2. Front and rear springs
3. Front and rear shock absorber / strut bumpstops
4. Front strut bearings and any related bushings
5. Rear shock bushings
6. Front and rear swaybar bushings

In some cases, inspections performed by the dealers revealed that additional components required replacement (items such as tie rods, other bushings, brake components, etc.). Once all items were replaced, a four-wheel alignment was performed. All alignment settings were within specifications established by the vehicle manufacturers.

The 2001 Toyota 4Runner was equipped with electronic stability control (Vehicle Skid Control, or "VSC") as standard equipment, whereas it was unavailable for previous model years. Since one Phase VI vehicle selection criteria was known crash data, NHTSA could not evaluate the 4Runner with enabled VSC, as crash data lags model year by approximately two years. However, Toyota was able to confirm the performance of the NHTSA-owned 2001 4Runner *with disabled VSC* would be identical to that expected from a 2000 model, a year for which crash data was available.

[4] The suspensions of the 2001 Toyota 4Runner and 2001 Chevrolet Blazer were not refurbished. In the opinion of the authors, replacement of suspension components was not necessary for these vehicles since they were purchased new by NHTSA in 2001 for Phase IV and V rollover research.

Table 3.1. Test Vehicle Descriptive Parameters (Baseline Condition, Sorted By Static Stability Factor In Descending Order, Per Vehicle Class).

Vehicle			Engine	GVWR (lbs)	Rear GAWR (lbs)	Miscellaneous Features	Wheelbase (in)	Mean Track Width (in)	Test Weight w/o outriggers (lbs)	Steering Ratio (deg/deg)	SSF Rollover Rating
Description	Model Year	Make/Model									
SUV	1998	Honda CR-V	2.0L T4	4165	2155	4-dr, 4WD, 4-spd auto	103.2	60.6	3371	18.6	★★★
SUV	1998	Chevrolet Tracker	1.6L I4	3307	1984	2-dr convertible, 4WD, 5-spd manual	86.5	54.9	2625	20.4	★★★
SUV	1997	Jeep Cherokee Sport	4.0L I6	4900	2700	4-dr, 4WD, 4-spd auto	101.3	58.2	3684	17.7	★★
SUV	2001*	Toyota 4Runner	3.4L V6	5250	3000	4-dr, 4WD, 4-spd auto, <u>disabled</u> VSC	105.3	59.5	4239	21.1	★★
SUV	1996	Acura SLX	3.2L V6	5510	3085	4-dr, 4WD, 4-spd auto	108.5	60.0	4467	21.1	★★
SUV	2001	Ford Explorer XLS	4.0L V6	5340	2950	4-dr, 4WD, 4-spd auto	111.8	58.8	4446	18.8	★★
SUV	2001	Ford Explorer Sport	4.0L V6	4760	2650	2-dr, RWD, 4-spd auto	102.1	58.6	4057	21.6	★★
SUV	2001	Chevrolet Blazer	4.3L V6	5000	2800	4-dr, RWD, 4-spd auto	107.1	54.6	3998	18.5	★
SUV	1995	Mitsubishi Montero	3.0L V6	5730	3640	4-dr, 4WD, 4-spd auto	107.2	56.0	4655	19.4	★
Pick-up	1992	Ford F-150	4.9L I6	5450	3166	RWD, 4-spd auto, std cab, long bed, dual fuel tanks	133.2	64.9	4397	19.3	★★★
Pick-up	1994	Chevrolet C1500	4.3L V6	6100	3686	RWD, 4-spd auto, std cab, long bed	131.4	64.2	4273	18.1	★★★
Pick-up	1997	Ford F-150	4.2L V6	6000	3600	RWD, 4-spd auto, std cab, long bed	138.3	65.3	4438	16.4	★★★
Pick-up	1995	Chevrolet K1500	5.0L V8	6100	3750	4WD, 4-spd auto, std cab, long bed	131.3	63.9	4856	17.6	★★★
Pick-up	1997	Ford Ranger	2.3L T4	4220	2384	RWD, 5-spd manual, std cab, std bed	108.3	57.1	3228	18.8	★★★
Pick-up	1997	Ford Ranger	3.0L V6	4960	2750	4WD, 5-spd manual, std cab, Sport Truck	108.3	57.9	3723	20.8	★★
Minivan	1998	Plymouth Voyager	2.4L T4	5000	2600	FWD, 4-spd auto, 7 passenger	113.8	63.6	3812	18.1	★★★★
Minivan	1995	Ford Windstar GL	3.8L V6	5132	2465	FWD, 4-spd auto, 7 passenger	121.0	63.8	3943	16.0	★★★★
Minivan	1994	Dodge Caravan	2.5L T4	5040	2544	FWD, 3-spd auto, 7 passenger	112.3	61.0	3616	18.0	★★★
Minivan	1995	Chevrolet Astro	4.3L V6	5950	3150	RWD, 4-spd auto, 8 passenger	111.1	65.4	4422	15.6	★★★
Minivan	1993	Ford Aerostar	3.0L V6	5000	2630	RWD, 4-spd auto, 7 passenger	118.8	61.0	3879	18.9	★★
Passenger Car	2002	Chevrolet Corvette	5.7L V8	3651	1875	2-dr coupe, RWD, 5-spd auto, Active Handling	104.3	61.6	3361	16.0	★★★★★
Passenger Car	1992	Honda Civic LX	1.5L T4	3315	1625	2-dr, FWD, 4-spd auto	103.2	58.2	2529	19.4	★★★★★
Passenger Car	1994	Ford Taurus	3.8L V6	4635	2170	4-dr, FWD, 3-spd auto	106.1	61.0	3407	16.2	★★★★
Passenger Car	1993	Chevrolet Caprice Classic	5.0L V8	5102	2600	4-dr, RWD, 4-spd auto	115.9	62.5	4097	17.1	★★★★
Passenger Car	1997	Chevrolet Metro	1.3L T4	2623	1235	2-dr hatchback, FWD, 3-spd auto	93.2	54.0	2057	21.1	★★★★
Passenger Car	1991	Chevrolet Cavalier	2.2L T4	3492	1591	2-dr, FWD, 3-spd auto	101.5	55.5	2728	16.0	★★★★

*The electronic stability control (VSC) installed on the model year 2001 4Runner was disabled during all tests performed in Phase VI. Since the only significant difference between model year 2000 and 2001 4Runners is the presence of stability control (not available in 2000, standard equipment in 2001), the performance of the 2001 model with disabled stability control is representative of an otherwise equivalent 2000 model.

For Phase VII testing, five vehicles were chosen from the Phase VI vehicle fleet. These vehicles were selected for use in this study because they best allowed the effects of alternative loading or steering angle scalar adjustment to be studied, as previously described in Section 2.1.5.

Calculation of the steering ratios (provided in eleventh column of Table 3.1) required handwheel and road wheel angle data. Using increments of 90 degrees, the handwheel was turned clockwise from zero to 450 degrees, then back to zero. At each increment, the road wheel angles of both front wheels were measured with low coefficient of friction suspension alignment plates. The process was repeated with counterclockwise steering. Data was plotted to check for hysteresis. Linear regressions were performed for each wheel to assess statistical correlation. The R-squared coefficients were greater than 0.994 for each front wheel, for all vehicles. The absolute values of the two regression line slopes were averaged to yield a final, overall steering ratio for each vehicle. Accurate determination of the steering ratio was important, as these values were later used in understeer gradient calculations.

3.2 Tires

3.2.1 Description

All tires used in Phase VI testing were new and inflated to the pressures recommended by each manufacturer on the vehicle identification placards. Due to the age (up to eleven years old) and mileage of the "used" Phase VI vehicles, the authors believed it was unlikely they were still equipped with the original equipment (OE) tires. To insure the proper tires were installed on the vehicles for testing, manufacturers of the "used" vehicles were asked to provide OE tire specifications. In some cases, obtaining tires of the same make, model, size, and DOT specification as those installed by the manufacturer as OE was not possible (e.g., some tires were out of production). In the event an OE tire was unavailable, the vehicle manufacturer was asked to recommend a contemporary equivalent. If the vehicle manufacturer was unable to provide such a recommendation, an OE tire manufacturer was contacted. For Phase VII testing, the size, load index, speed rating, make, and model of the tires were identical to those used in Phase VI. Appendix Table A.1 presents the tire information for each vehicle used in Phases VI and VII.

3.2.2 Break-In Procedure

Prior to actual testing, the tires were "scrubbed in" to wear away mold sheen and be brought up to operating temperature. This was accomplished by driving the vehicle around a circle 100 feet in diameter at a speed that produced a lateral acceleration of approximately 0.5 to 0.6 g. Using this circle, three clockwise laps were followed by three counterclockwise laps. Once these six laps were complete, the driver input sinusoidal steering with a magnitude capable of producing a lateral acceleration of 0.5 to 0.6 g (δ_{SS}) at a frequency of 1 Hz for 10 cycles while maintaining a vehicle speed of 35 mph. A total of four passes using sinusoidal steering were used. The handwheel magnitude of the final cycle of the final pass was twice that of δ_{SS}. A programmable steering machine was used to input all sinusoidal steering used during the break-in procedure.

3.2.3 Mounting Technique

With the exception of the ultra low-profile run-flat tires installed on the Chevrolet Corvette, no lubricant was used when mounting tires to the rims used for testing. This was done to eliminate the possibility of tire lubricant contributing to debeading.

3.2.4 Frequency of Changes

To minimize the effects of tire wear on vehicle response and rollover propensity, frequent tire changes were utilized. For each loading condition, the following guidelines were followed:

- One set of tires was used for each Slowly Increasing Steer test series. Each series was comprised of left and right steer tests.

- One set of tires was used per J-Turn test series. Each series was comprised of left and right steer tests.

- One set of tires was used per Road Edge Recovery test series. Each series was comprised of left and right steer tests.

3.2.5 Use of Inner Tubes

Road Edge Recovery maneuvers have been shown to produce debeading of the outside front and rear tires [1]. The occurrence of debeads can result in significant damage to the test surface. During the conduct of Phase IV rollover research NHTSA concluded the easiest, most cost effective way to prevent debeads was to use inner tubes designed for radial tires. As such, inner tubes were installed prior to every Road Edge Recovery test, one inner tube for each of the vehicles four tires. Inner tubes were appropriately sized for the test vehicle's tires.

When the Phase VI test plan was conceived, the authors did not foresee the J-Turn maneuver as being capable of producing a debead situation (no debeads occurred during J-Turns previously performed in Phases I-A, I-B, II, III-A, III-B, IV, or V). Early in Phase VI, however, use of the J-Turn maneuver produced a debead during the evaluation of the Dodge Caravan. The Phase VI test plan was thus amended and required all subsequent J-Turns to be performed with one inner tube installed in each of the vehicles four tires[5].

3.2.6 Definition of Rim-To-Pavement Contact and Tire Debeading

NHTSA's current J-Turn and Road Edge Recovery maneuvers impose severe demands on test vehicles. As such, rim-to-pavement contact and tire debeading occasionally occur. In this report, "rim-to-pavement contact" means some part of the rim made contact with the test surface but does not necessarily mean a tire debead occurred. When it occurred, such contact was

[5] The Toyota 4Runner, Chevrolet Blazer, Ford Explorers, Plymouth Voyager, Jeep Cherokee, Acura SLX and Mitsubishi Montero were not evaluated with inner tubes during J-Turn maneuvers because they were evaluated prior to the Dodge Caravan tire debead. J-Turn testing of these vehicles did not result in rim-to-pavement contact or tire debeading.

always apparent to the experimenter because the outside lip of the rim was physically damaged (i.e., scraped). When the term “debead” is used in this report, it does not simply refer to the bead of the tire moving over the rim’s safety hump, as shown in Figure 3.1. In this example, the bead of the left front tire has obviously unseated. However, since the inner tube installed in this tire prevented any loss of air pressure, no rim-to-pavement contact was detected. At the conclusion of this particular test, the tire reseated itself, and the remaining tests in the series were performed.

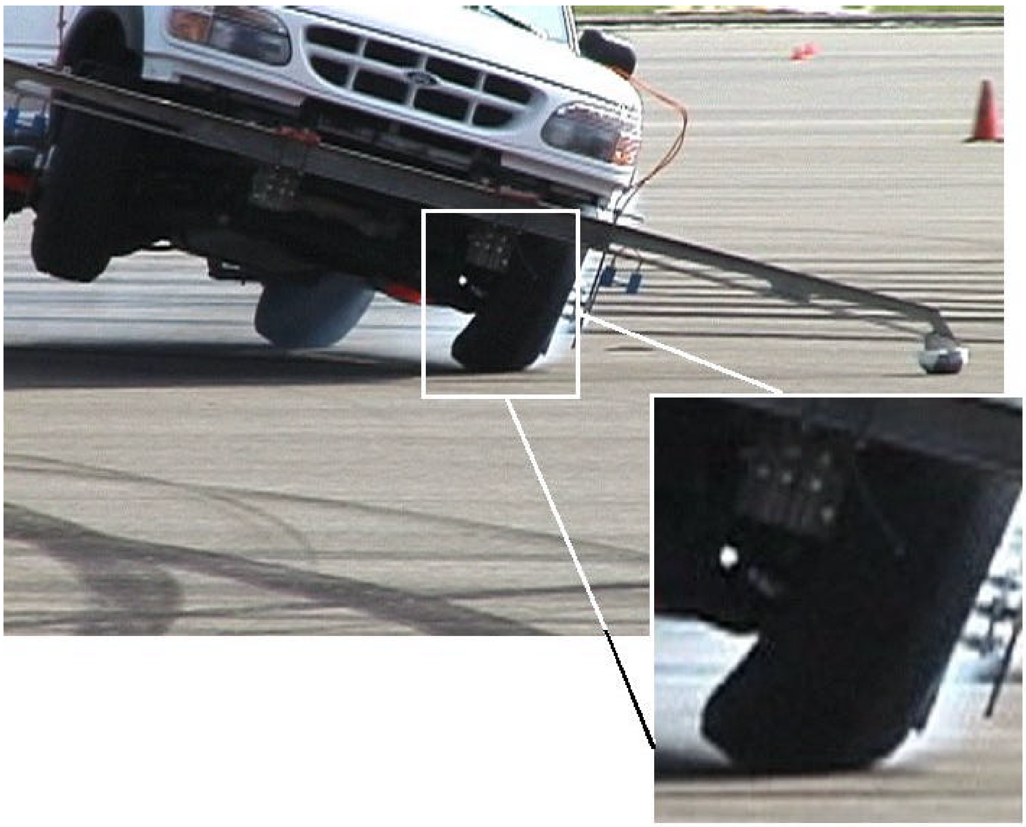


Figure 3.1. Example of a left front tire bead unseat. As defined for use in this report, this was not considered to be a “debead.”

For use in this report, the authors define “debead” as a situation in which the tire bead unseat results in a sudden loss of all air pressure and abrupt rim-to-pavement contact. If the tire has an inner tube installed, “debead” means that the bead unseat was so severe that the inner tube ruptured and all pressure was lost. Unlike most rim-to-pavement contacts, debeading can result in severe damage to the test surface and necessitate replacement of the affected wheel. Figure 3.2 presents an example of a tire debead.

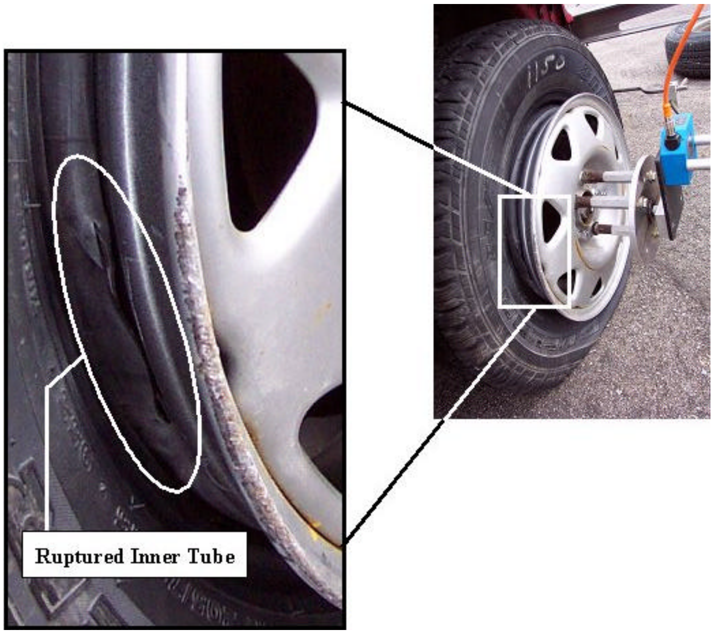


Figure 3.2. Example of a tire debead with a ruptured inner tube.

3.3 Vehicle Load Configurations

The Rollover Resistance tests performed in Phase VI testing used two loading configurations: Nominal Load and Maximum Occupancy. A description of each configuration is provided below. In both conditions, the vehicle was fully fueled.

For Phase VII testing, each vehicle was tested in the Nominal Load configuration. The Chevrolet Astro and Ford Aerostar were also evaluated with the newly developed "Multi-Passenger Configuration." In both conditions, the vehicles were fully fueled.

Table 3.3, presented at the end of this section, compares baseline SSF and pitch, roll, and yaw inertia measurements of each vehicle to those measured in the two Rollover Resistance load configurations. All values presented in this table are expressed as percentages. Values contained within parentheses indicate reductions.

3.3.1 Nominal Load

The Nominal Load configuration consisted of the driver, instrumentation, a steering machine, and titanium outriggers. Each vehicle was fully fueled. To quantify the influence of the Nominal Load on SSF and mass moments of inertia, each vehicle was tested on the Vehicle Inertia Measurement Facility (VIMF) at SEA, Inc. Results from tests performed in the Nominal Load configuration were compared with those measured in the Baseline condition. Appendix Tables A.2 and A.3 summarize the Baseline and Nominal Load data, respectively. Note that the Nominal Load data presented in this table includes the effects of instrumentation.

The Nominal Load configuration increased the SSF (by lowering the center of gravity) and increased each mass moment of inertia of every test vehicle. The SSFs increased 1.2 percent (1994 Chevrolet C1500 and 1997 Ford F150) to 4.3 percent (Chevrolet Metro), and averaged 2.6 percent overall. Increases in pitch inertia ranged from 7.1 percent (Toyota 4Runner) to 25.2 percent (Chevrolet Metro), averaging 14.3 percent overall. Roll inertia increased 9.9 percent (Chevrolet C1500) to 26.2 percent (Chevrolet Metro), and averaged 15.4 percent overall. Yaw inertia increased 9.1 percent (Toyota 4Runner) to 27.3 percent (Chevrolet Metro), averaging 15.5 percent overall.

3.3.2 Maximum Occupancy Configuration (Phase VI only)

In addition to the equipment used in the Nominal Load configuration, Maximum Occupancy loading generally used water dummies positioned at each seating position for which an adult passenger may be restrained with a seatbelt. Water dummies were not installed at any front seat position. This not only included the passenger-side front seat, but the middle seat if the vehicle was equipped with a bench seat. Figure 3.3 shows a common rear seat configuration. In this figure, three water dummies occupy the three rear seating positions of a 1996 Acura SLX.

Figure 3.3. Three water dummies placed in the rear seating positions of a 1996 Acura SLX.

Six Phase VI test vehicles were pickups capable of seating only front seat occupants. Since no Maximum Occupancy condition existed for these vehicles, an alternative condition was created. This alternative loading was used in an attempt to impose a rollover resistance test condition of approximately equal severity to that imposed by the "conventional" Maximum Occupancy condition on a dimensionally similar sport utility vehicle. For the Chevrolet C1500 and K1500 (1994 and 1995 model years, respectively), as well as for the 1992 and 1997 model year Ford F150s, two rows of three water dummies were placed in the beds so as to emulate the center and rear row seating positions of a 1994 Chevrolet Suburban (see Figures 3.4 and 3.5). For the 1997 Ford Rangers (4x2 and 4x4), one row of two water dummies was placed in the beds so as to emulate the rear row seating position of a 2001 Ford Explorer 4x2.

Figure 3.4. Comparison of a 1994 Chevrolet Suburban (top) and 1995 K1500 (bottom). Note the similarity of the Suburban's actual rear seats and the simulated rear seating positions used for the K1500.

Figure 3.5. Six water dummies secured in the bed of a 1995 Chevrolet K1500 pickup.

When completely filled, a water dummy weighs 175 lbs. For some vehicles, use of completely filled water dummies in every designated seating position caused the front and/or rear Gross Axle Weight Rating (GAWR) and/or vehicle Gross Vehicle Weight Rating (GVWR) to be exceeded. This situation required the use of partially filled water dummies. "Partially full" water dummies weighed 108 lbs, a weight similar to that of a 5^{th} percentile female HYBRID dummy. To prevent "slosh" from confounding test outcome, sections of low density Styrofoam were used to uniformly displace the water. Table 3.2 provides a summary of the longitudinal and vertical C.G. positions and mass moments of inertia for the completely filled and partially filled water dummies used in this study. The C.G. values are calculated using geometric approximations of each water dummy (two rectangle boxes). The mass moments of inertia were measured directly at SEA, Inc. on their Small Parts Inertia Tester.

Table 3.2. Water Dummy Calculated / Measured Parameters.

Measurement	Completely Full	Partially Full
Weight	175.0 lbs	108.0 lbs
Longitudinal C.G. Location (fore of seat back)	7.75 inches	7.75 inches
Lateral C.G. Location	Centerline of Dummy	Centerline of Dummy
Vertical C.G. Height (above seat)	11.0 inches	11.0 inches
Roll Moment of Inertia About C.G.	3.10 ft-lb-s^2	1.82 ft-lb-s^2
Pitch Moment of Inertia About C.G.	2.99 ft-lb-s^2	1.81 ft-lb-s^2
Yaw Moment of Inertia About C.G.	1.74 ft-lb-s^2	1.04 ft-lb-s^2

Appendix Table A.4 summarizes the Maximum Occupancy VIMF data. For most vehicles, the Maximum Occupancy configuration decreased the SSF (raised the center of gravity height) and increased each mass moment of inertia. Changes in SSF ranged from an increase of 3.6 percent (Chevrolet Caprice) to a 5.0 percent decrease (1997 Ford F150), and averaged 0.8 percent overall. Increases in pitch inertia ranged from 13.9 percent (Toyota 4Runner) to 38.3 percent (Ford Windstar), averaging 26.9 percent overall. Roll inertia increased 17.5 percent (Ford Explorer XLS) to 37.0 percent (Chevrolet Tracker), and averaged 24.1 percent overall. Yaw inertia increased 15.9 percent (Toyota 4Runner) to 37.7 percent (Chevrolet Metro), averaging 27.0 percent overall.

Note that despite the use of two kinds of water dummies (full and partially full), the experimenters were unable to achieve the Maximum Occupancy criterion for each test vehicle without exceeding front, rear, and/or vehicle weight ratings. An explanation of how these situations were resolved is provided on a vehicle-by-vehicle basis:

1998 Honda CR-V. When a full water dummy was placed in each of the three designated rear seating positions, the front GAWR was exceeded. To remedy this situation experimenters explored the use of a variety of different water dummy configurations. Even a configuration of two partially filled water dummies (≈216 lbs) was unable to reduce weight at the front axle to or below its GAWR. Two full water dummies were ultimately used (≈356 lbs) as this option allowed the vehicle to be loaded close to its front GAWR while still being evaluated in a configuration used by six other Phase VI test vehicles. This option resulted in the vehicle exceeding its front GAWR by 30 lbs (1.5 percent).

1995 Mitsubishi Montero. When a full water dummy was placed in each of the five designated rear seating positions, the rear GAWR was exceeded. To remedy this situation, the experimenters used two partially filled water dummies in the two rear-most seating positions. This loading allowed the weight of the rear axle to fall below that of the vehicle's rear GAWR.

1992 Ford F150. When a full water dummy was placed in each of the six designated "rear seating positions," the GVWR was exceeded. To remedy this situation, the experimenters used one partially filled water dummy in each seating position. This loading allowed the weight of the vehicle to be reduced slightly below that of the GVWR (1.0 percent less) in the most uniform way possible.

1993 Ford Aerostar. When a full water dummy was placed in each of the five designated rear seating positions, the GVWR was exceeded. To remedy this situation, the experimenters used two partially filled water dummies in the second row seating positions, and three full water dummies in the rear-most third seating row. This loading allowed the weight of the vehicle to be reduced to approximately that of the GVWR, however GVWR was still exceeded by 50 lbs (1.0 percent).

1992 Honda Civic. When a full water dummy was placed in each of the three designated rear seating positions, the front GAWR and vehicle GVWR were both exceeded. To remedy this situation, two options were available to the experimenters: use three partially filled water dummies (≈324 lbs) or two full water dummies (≈356 lbs). Two full water dummies were ultimately used, as this option allowed for the inclusion of the most weight while respecting all weight rating limits.

1991 Chevrolet Cavalier. When a full water dummy was placed in each of the three designated rear seating positions the front GAWR and vehicle GVWR were both exceeded. To remedy this situation, three options were available to the experimenters: use three partially filled water dummies, two full water dummies, or some combination of full and partially filled water dummies. None of these options were capable of reducing the weight over the front axle to or below its GAWR. Two full water dummies were ultimately used, as this option allowed the vehicle weight to drop below GVWR with the smallest weight reduction, and allowed the vehicle to be evaluated in a configuration used by six other Phase VI test vehicles. However, this option still resulted in the vehicle exceeding its front GAWR by 29 lbs (1.5 percent).

1997 Chevrolet Metro. When a full water dummy was placed in each of the two designated rear seating positions, the front and rear GAWRs, as well as the vehicle GVWR, were exceeded.

To remedy this situation, only one option was available to the experimenters: use two partially filled water dummies. This option still resulted in the vehicle exceeding two weight ratings. The front GAWR and vehicle GVWR were exceeded by 44 lbs (3.1 percent) and 3 lbs (0.1 percent), respectively.

2002 Chevrolet Corvette. No Maximum Occupancy configuration, or comparable alternative, was used to evaluate the Chevrolet Corvette. This test vehicle was only capable of seating two occupants (i.e., the driver and one passenger); therefore, the Maximum Occupancy condition was omitted.

3.3.3 Multi-Passenger Configuration (Phase VII only)

The Multi-Passenger configuration was developed for testing during Phase VII. In addition to the equipment used in the Nominal Load configuration, tests were performed with three full water dummies (weighing 175 lbs each) positioned in each second-row seating position for which an adult passenger may be restrained with a seatbelt. The Chevrolet Astro could be evaluated in this condition because its second seating row included three seating positions. In the case of the Ford Aerostar, the second row was only designed for two passengers, therefore only two water dummies were positioned in the second row. The third dummy was placed in the center of the third seating row. Water dummies were not installed in any front seat position.

The use of three water dummies allowed NHTSA to investigate how the use of a "standard" occupancy condition (i.e., the use of three water dummies, regardless of seating capacity[6]) may change J-Turn and Road Edge Recovery test outcome from that observed with the Phase VI "Maximum Occupancy" configuration. VIMF measurements for the Chevrolet Astro and Ford Aerostar in the Multi-Passenger Configuration were not taken.

[6] NHTSA's improved water dummy specification criteria is defined in Chapter 9.

Table 3.3. Percent Change from Baseline Condition (Sorted By Baseline SSF In Descending Order, Per Vehicle Class).

Vehicle	SSF		Pitch Inertia		Roll Inertia		Yaw Inertia	
	Nominal Load	Maximum Occupancy	Nominal Load	Maximum Occupancy	Nominal Load	Maximum Occupancy	Nominal Load	Maximum Occupancy
1998 Honda CR-V	2.3	0.2	14.1	20.1	12.5	18.3	15.3	21.1
1998 Chevrolet Tracker	2.0	(2.3)	17.5	30.9	23.7	**37.0**	20.4	31.3
1997 Jeep Cherokee Sport	3.7	1.6	18.4	25.9	21.2	28.1	19.5	27.9
2001 Toyota 4Runner*	2.3	(1.4)	**7.1**	**13.9**	20.7	25.1	**9.1**	**15.9**
1996 Acura SLX	2.7	(1.5)	12.0	16.5	11.9	18.4	12.9	18.2
2001 Ford Explorer XLS	2.6	(0.6)	13.4	19.3	12.3	**17.5**	14.7	20.9
2001 Ford Explorer Sport	1.8	(0.3)	10.9	18.5	12.2	18.9	14.9	19.4
2001 Chevrolet Blazer	3.5	0.9	13.5	20.6	21.9	28.4	14.6	21.0
1995 Mitsubishi Montero	2.8	(0.7)	11.9	22.0	11.9	20.1	13.6	23.9
1992 Ford F-150	1.6	(0.5)	10.3	23.8	16.3	32.6	10.3	23.1
1994 Chevrolet C1500	**1.2**	(3.8)	10.2	31.6	**9.9**	24.6	10.0	28.9
1997 Ford F-150	**1.2**	**(5.0)**	10.3	32.3	10.3	21.2	11.4	31.8
1995 Chevrolet K1500	1.4	(3.8)	8.6	25.7	12.0	20.4	9.3	24.5
1997 Ford Ranger 4x2	2.0	(1.1)	14.8	26.1	15.2	21.7	16.3	26.0
1997 Ford Ranger 4x4	1.9	(1.7)	16.0	26.8	14.4	22.0	17.2	26.8
1998 Plymouth Voyager	3.2	(2.1)	13.8	35.7	12.6	21.3	14.9	34.4
1995 Ford Windstar GL	2.6	(2.9)	16.4	**38.3**	13.2	22.1	16.8	36.9
1994 Dodge Caravan	4.0	(0.8)	15.2	38.0	12.0	32.0	16.4	37.4
1995 Chevrolet Astro	1.9	**(5.0)**	12.4	27.4	11.4	23.5	13.3	27.2
1993 Ford Aerostar	2.4	(4.2)	17.5	36.5	14.0	22.9	18.8	36.6
2002 Chevrolet Corvette	2.1	N/A	19.1	N/A	13.8	N/A	19.2	N/A
1992 Honda Civic LX	3.1	2.8	20.0	32.1	20.6	26.1	21.1	31.5
1994 Ford Taurus	2.3	2.6	18.5	31.4	16.0	23.1	19.1	30.5
1993 Chevrolet Caprice Classic	3.7	**3.6**	10.2	17.7	17.0	24.1	11.0	17.5
1997 Chevrolet Metro	**4.3**	2.9	**25.2**	35.4	**26.2**	30.2	**27.3**	**37.7**
1991 Chevrolet Cavalier	3.9	3.2	14.6	24.8	17.7	24.0	15.9	25.6

Note: Bold values indicated the high and low percent changes of each column.

*The electronic stability control (VSC) installed on the model year 2001 4Runner was disabled during all tests performed in Phase VI. Since the only significant difference between model year 2000 and 2001 4Runners is the presence of stability control (not available in 2000, standard equipment in 2001), the performance of the 2001 model with disabled stability control is representative of an otherwise equivalent 2000 model.

3.4 Installation of Outriggers

The outriggers used in Phases VI and VII were designed to minimize the effect of their installation on test vehicle roll inertia. Each beam was CNC machined from extruded 6AL-4V titanium I-beams. A typical installation is featured in Figure 3.6.

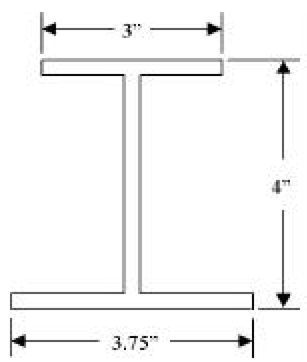
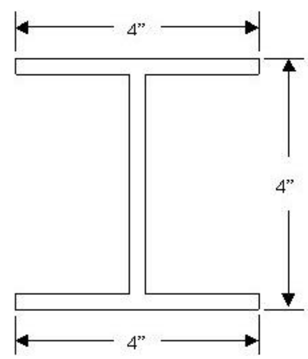
Figure 3.6. Typical installation of NHTSA's "standard" titanium outriggers. The 6-component wheel load transducers seen in these pictures were not used in Phases VI or VII.

The outriggers were attached to the front and rear bumper attachment points with steel brackets. Depending on the weight of the vehicle, one of two outrigger designs was used. With the exception of the Ford Taurus[7], if a test vehicle weighed <3500 lbs in the baseline condition, the "short" outriggers were used. If the test vehicle weighed ∃3500 lbs in the baseline condition, the "standard" outriggers were used. Table 3.4 compares the length, weight, cross-sections, and

[7] Outrigger selection was initially based on the test weight of the vehicle in the Nominal Load configuration. This was later changed to the vehicle weight in the baseline condition. Using the revised selection criteria, the Taurus would have been evaluated with the "short" outriggers. The authors do not believe the outcome of the Rollover Resistance tests was adversely affected by this discrepancy. No two-wheel lift was produced during tests performed with the "standard" outriggers, and it would not be expected to occur had the "short" outriggers been installed.

mass moments of inertia of the short and standard outriggers, and shows which outrigger was installed on each test vehicle. Detailed schematics of these outriggers are available in [10].

Table 3.4. Phase VI Outrigger Specifications and Installation Summary.

Description	Short	Standard
Length	135 inches	147 inches
Flange/Web Thickness	0.25 inches	0.25 inches
Weight	57.5 lbs	63.3 lbs
Cross-section		
Moment of Inertia About Pitch Axis (Through Outrigger C.G.)	≈ 0	≈ 0
Moment of Inertia About Roll and Yaw Axes (Through Outrigger C.G.)	19.6 ft-lb-s^2	24.2 ft-lb-s^2
Vertical C.G. Location	2.2 inches (below top of the top flange)	2.4 inches (below top of the top flange)
Installation Summary	1998 Chevrolet Tracker 1998 Honda CR-V 1997 Ford Ranger 4x2 2002 Chevrolet Corvette 1991 Chevrolet Cavalier 1997 Chevrolet Metro 1992 Honda Civic	1996 Acura SLX 2001 Ford Explorer Sport 2001 Ford Explorer XLS 1997 Jeep Cherokee Sport 2001 Toyota 4Runner 2001 Chevrolet Blazer 1995 Mitsubishi Montero 1995 Chevrolet K1500 1994 Chevrolet C1500 1997 Ford F150 1992 Ford F150 1997 Ford Ranger 4x4 1995 Ford Windstar 1998 Plymouth Voyager 1995 Chevrolet Astro 1994 Dodge Caravan 1993 Ford Aerostar 1993 Chevrolet Caprice 1994 Ford Taurus

4.0 INSTRUMENTATION

Each Phase VI and VII test vehicle was similarly instrumented with sensors, a data acquisition system, and a programmable steering machine. This chapter briefly describes the test equipment, and how it was utilized.

4.1 Sensors and Sensor Locations

Table 4.1 describes the sensors used to measure vehicle responses. Sensors are listed with the data channel measured in the first column of the table. Additional columns list the sensor type, sensor range, sensor manufacturer, and sensor model number.

Table 4.1. Test Vehicle Sensor Information.

Data Measured	Type	Range	Manufacturer	Model Number
Handwheel Angle	Angle Encoder	Infinite	Automotive Testing, Inc.	Integral with ATI Steering Machine
Brake Pedal Force	Load Cell	0-300 lbf	GSE Inc.	4351
Longitudinal, Lateral, and Vertical Acceleration Roll, Yaw, and Pitch Rate	Multi-Axis Inertial Sensing System	Accelerometers: ±2 g Angular Rate Sensors: ±100°/s	BEI Technologies, Inc. Systron Donner Inertial Division	MotionPak Multi-Axis Inertial Sensing System MP-1
Left and Right Side Vehicle Ride Height	Ultrasonic Distance Measuring System	4-40 inches	Massa Products Corp.	M-5000 / 220 kHz
Vehicle Speed	Radar Speed Sensor	0.1-125 mph	B+S Software und Messtechnik GmbH	DRS-6
Wheel Lift (via resolution of two measured distances spaced a known distance apart)	Analog Displacement Measuring System (Infrared; 880nm)	13.8 - 33.5 inches; 11.8-51.2 inches	Wenglor Sensors Ltd.	HT 66MGV80; HT 77MGV80

Handwheel position was recorded with an angle encoder integral with the programmable steering machine.

Brake pedal force was measured with a load cell transducer attached to the face of the brake pedal. While brake pedal force was not explicitly required by any test performed in Phases VI or VII, it was important to monitor the driver’s braking activity during testing. If the driver applied force to the brake pedal during the conduct of any test, the test was invalid.

A multi-axis inertial sensing system was used to measure linear accelerations and roll, pitch, and yaw angular rates. The system was placed near the vehicle’s center of gravity (C.G.) so as to minimize roll, pitch, and yaw effects. Since it was not possible to position the accelerometers precisely at every vehicle's C.G. for each loading condition, sensor outputs were corrected to translate the motion of the vehicle at the measured location to that which occurred at the actual C.G. (during post-processing of the data). The equations used for these corrections were derived from equations of general relative acceleration for a translating reference frame and use the SAE Convention for Vehicle Dynamics Coordinate Systems. The sensing system did not provide inertial stabilization of its accelerometers. Therefore, lateral acceleration was also corrected for vehicle roll angle during data post processing using the techniques explained in [1].

An ultrasonic distance measurement system was used to collect left and right side vehicle ride heights for the purpose of calculating vehicle roll angle. One ultrasonic ranging module was mounted on each side of a vehicle and were positioned at each vehicle's longitudinal center of gravity. Vehicle roll angle was computed from the output of the two sensors and the roll rate was measured by the multi-axis inertial sensing system. Reference [1] presents the technique used.

Vehicle speed was measured with a non-contact speed sensor placed at the center rear of each vehicle. Sensor outputs were transmitted not only to the data acquisition system, but also to a dashboard display unit. This allowed the driver to accurately monitor vehicle speed.

Wheel lift was measured individually with two infrared height sensors attached to spindles installed at the wheel, as shown in Figure 4.1. Using basic trigonometry, the output of the two sensors was used to resolve the camber angle of the wheel, and remove its influence from the uncorrected height sensor output. Reference [11] presents the technique used by NHTSA to install and calibrate these sensors.

Figure 4.1. Infrared height sensors used to measure wheel lift.

4.2 Programmable Steering Machine

A programmable steering machine produced by Automotive Testing, Inc. (ATI) was used to provide steering inputs for all Phase VI and VII test maneuvers. Descriptions of the steering machine, including features and technical specifications, have been previously documented and are available in [12,13].

The steering machine was configured to reverse the direction of steer close to maximum roll angle during Road Edge Recovery maneuvers. This is accomplished by monitoring roll rate zero crossings. When roll rate goes to zero, roll angle is at a maximum (since roll rate is the derivative of roll angle). Specifically, a roll rate window comparator set to ∀ 1.5 degrees per second was used to command handwheel reversals. When counterclockwise steering is performed, the vehicle rolls in the clockwise direction. As maximum roll angle is achieved, roll rate approaches zero by first passing through the +1.5 deg/sec threshold of the window comparator, thereby commanding a clockwise handwheel reversal. Conversely, when clockwise steering is performed, the vehicle rolls in a counterclockwise direction. As maximum roll angle is achieved, roll rate approaches zero by first passing through the -1.5 deg/sec threshold of the window comparator, thereby commanding a counterclockwise handwheel reversal.

4.3 Data Acquisition

In-vehicle data acquisition systems, comprised of ruggedized industrial computers, recorded outputs from the previously mentioned sensors during the conduct of test maneuvers. All data was sampled at a rate of 200 Hz.

The computers employed the DAS-64 data acquisition software developed by the NHTSA's VRTC. Analog Devices Inc. 3B series signal conditioners were employed to condition data signals from all transducers listed in Table 4.1. Measurement Computing Corporation PCI-DAS6402/16 boards digitized analog signals at a collective rate of 200 kHz. Test drivers initiated data collection prior to the start of maneuvers performed with the steering machine.

Signal conditioning consisted of amplification, anti-alias filtering, and digitizing. Amplifier gains were selected to maximize the signal-to-noise ratio of the digitized data. Filtering was performed with two-pole low-pass Butterworth filters with nominal cutoff frequencies selected to prevent aliasing. At a nominal cutoff frequency of 15 Hz, the calculated breakpoint frequencies were 18 and 19 Hz for the first and second poles respectively. A higher nominal cutoff frequency of 1800 Hz (1800 Hz at pole 1 and 1900 Hz at pole 2) was used on the handwheel angle channel.

4.4 Post Processing Filters

Most sensor data were filtered in post-processing with 6-Hz 12-pole, 2-pass, phaseless digital Butterworth filters using Matlab software. Wheel lift height measurements were filtered with 200 ms, one-pass, digital running average filters.

5.0 TEST MANEUVERS

The Rollover Resistance tests performed in Phases VI and VII used three maneuvers: the Slowly Increasing Steer, the NHTSA J-Turn, and the NHTSA Road Edge Recovery. This chapter describes each test maneuver, and describes how it was performed.

5.1 Slowly Increasing Steer

Characterization maneuvers are used to provide vehicle-specific data for some fundamental performance metrics. Such maneuvers are not intended to produce two-wheel lift. The only Characterization maneuver used in this study was the Slowly Increasing Steer maneuver.

The Slowly Increasing Steer maneuver was used to characterize the lateral dynamics of each vehicle, and was based on the "Constant Speed, Variable Steer" test defined in SAE J266 [14]. Although Slowly Increasing Steer tests can be used to provide important handling information, NHTSA's Rollover Resistance tests only require the data output from the maneuver to define handwheel input magnitudes. For the sake of brevity, this paper does not discuss how the Slowly Increasing Steer maneuver pertains to the assessment of handling. This topic will be addressed in a later report.

To begin this maneuver, the vehicle was driven in a straight line at 50 mph. The driver was instructed to maintain as constant a test speed as possible before, during, and after the steering inputs using smooth throttle modulation. At time zero, handwheel position was linearly increased from zero to 270 degrees at a rate 13.5 degrees per second, as shown in Figure 5.1. Handwheel position was held constant at 270 degrees for two seconds, after which the maneuver was concluded. The handwheel was then returned to zero as a convenience to the driver. The maneuver was performed to the left and to the right. Three repetitions of each test condition were performed.

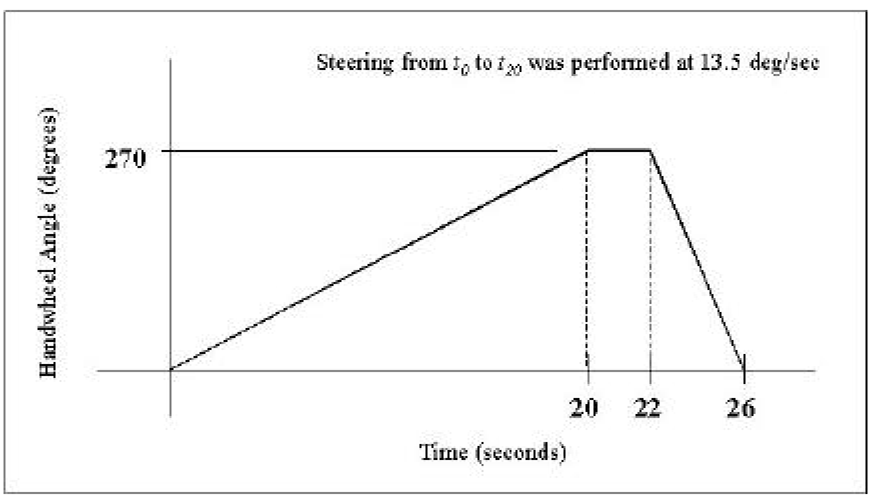


Figure 5.1. Slowly Increasing Steer maneuver description.

When lateral acceleration data collected during Slowly Increasing Steer tests was plotted with respect to time, a first order polynomial best-fit line was found to accurately describe the data from 0.1 to 0.4 g. NHTSA defines this as the linear range of the lateral acceleration response. A simple linear regression was used to describe how representative the best-fit line described the test data. Using the slope of the best-fit line, the average of handwheel positions at 0.3 g was calculated using data from each of the six Slowly Increasing Steer tests performed for each vehicle. This average handwheel position was used to calculate NHTSA J-Turn and Road Edge Recovery steering inputs, as described in the next two sections of this report.

5.2 NHTSA J-Turn

The NHTSA J-Turn is one of the most basic of all maneuvers used to evaluate dynamic rollover propensity (a single step-steer input). Given the right set of circumstances, it is possible for an actual driver to input J-Turn maneuver steering while driving on cloverleaf entrance/exit ramp, or while driving on a tightly curved road at substantial speed. Of the nine Rollover Resistance maneuvers studied in Phase IV, the J-Turn was one of only four maneuvers to receive a rating of "Satisfactory" or better in each of the four maneuver evaluation factors (Objectivity and Repeatability, Performability, Discriminatory Capability, and Appearance of Reality). The handwheel input rates and magnitudes of the NHTSA J-Turn are believed to be within the capabilities of an actual driver.

To begin the maneuver, the vehicle was driven in a straight line at a speed slightly greater than the desired entrance speed. The driver released the throttle, and when at the target speed, input the handwheel commands described in Figure 5.2 using the steering machine. Following completion of the handwheel ramp, handwheel position was maintained for four seconds. As a convenience to the test driver, the handwheel was then returned to zero.

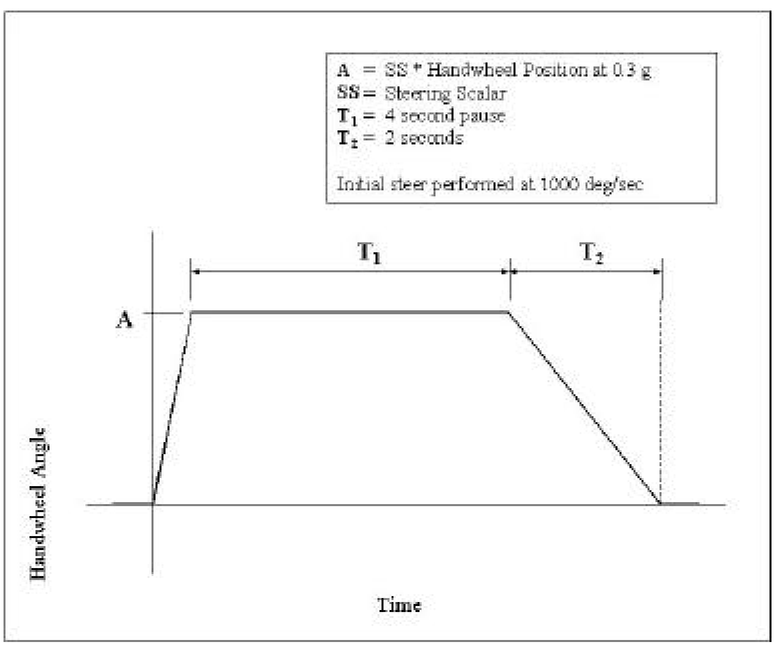


Figure 5.2. NHTSA J-Turn maneuver description.

J-Turn handwheel magnitudes were calculated by multiplying the handwheel angle producing an average of 0.3 g in the Slowly Increasing Steer maneuver by a scalar. In Phase VI testing, the scalar magnitude was 8.0, but in Phase VII, it was varied (increased or decreased by an integer value) so as to investigate the effect of the magnitude of steer on maneuver severity. Regardless of what steering scalar was used, the handwheel rate was always 1000 degrees per second for all test vehicles. Summaries of the J-Turn handwheel angles used in Phases VI and VII are presented in Tables 5.1 and 5.2, respectively. These tables are located at the end of this chapter.

The nominal maneuver entrance speeds used in the J-Turn maneuver ranged from 35 to 60 mph, and were increased in 5 mph increments until a termination condition was achieved. Termination conditions included two-wheel lift or completion of a test performed at the maximum maneuver entrance speed without two-wheel lift. If two-wheel lift was observed, a downward iteration of vehicle speed was used in 1 mph increments until lift was no longer detected. Once the lowest speed for which two-wheel lift could be detected was isolated, two additional J-Turns were performed at that speed to monitor two-wheel lift repeatability. These termination conditions may be modified, given the occurrence of tire debeading and/or rim-to-pavement contact. This will be discussed in further detail in Chapter 7.

5.3 NHTSA Road Edge Recovery

The handwheel inputs defining the Road Edge Recovery maneuver approximate the steering a startled driver might use in an effort to regain lane position on a two-lane road after dropping two wheels off onto the shoulder. Of the nine Rollover Resistance maneuvers studied in Phase IV, only the Road Edge Recovery maneuver received "Excellent" ratings in each of the four maneuver evaluation factors (Objectivity and Repeatability, Performability, Discriminatory Capability, and Appearance of Reality). NHTSA considers the Road Edge Recovery to be the best overall maneuver for evaluating dynamic rollover propensity. The handwheel input rates and magnitudes of the Road Edge Recovery are believed to be within the capabilities of an actual driver.

To begin the maneuver, the vehicle was driven in a straight line at a speed slightly greater than the desired entrance speed. The driver released the throttle, and when at the target speed, initiated the handwheel commands described in Figure 5.3 using the steering machine. Road Edge Recovery handwheel reversals were automatically initiated by the steering machine via use of a roll rate feedback control loop. After the completion of the initial steer, the steering machine held the handwheel angle constant until the magnitude of the roll rate signal (transmitted from a roll rate sensor installed near the test vehicle's center of gravity) was approximately 1.5 degrees per second. If a counterclockwise initial steer was input, the steering reversal following completion of the first handwheel ramp was to occur when the roll velocity of the vehicle was 1.5 degrees per second. If a clockwise initial steer was input, the steering reversal following completion of the first handwheel ramp occurred when the roll velocity of the vehicle was -1.5 degrees per second. The pause from the completion of the initial steering ramp to the initiation of the steering reversal is referred to as "dwell time" in this report (see "T1" in Figure 5.3). Following completion of the countersteer, handwheel position was maintained for three seconds. As a convenience to the test driver, the handwheel was then returned to zero.

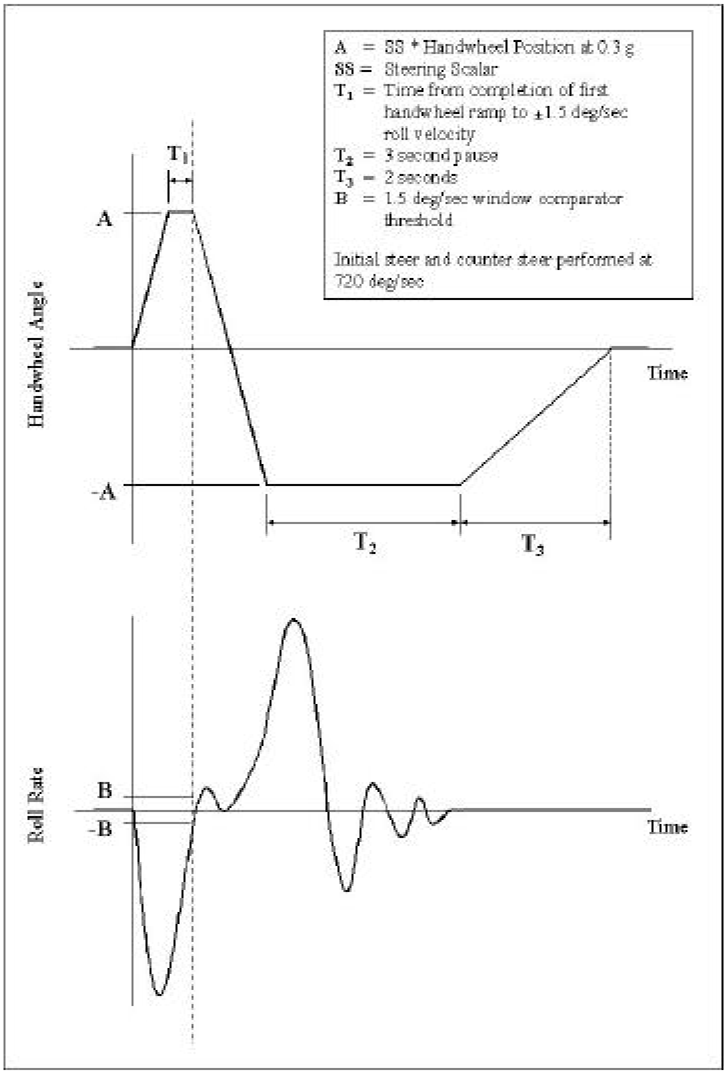


Figure 5.3. NHTSA Road Edge Recovery maneuver description.

In a manner similar to that used for the J-Turn, Road Edge Recovery handwheel magnitudes were calculated by multiplying the handwheel angle producing an average of 0.3 g in the Slowly Increasing Steer maneuver by a scalar. In Phase VI testing, the scalar magnitude was 6.5, but in Phase VII, it was varied (increased or decreased by an integer value) so as to investigate the effect of the magnitude of steer on maneuver severity. Regardless of what steering scalar was used, the handwheel rates of the initial steer and countersteer were always 720 degrees per second. Summaries of the Road Edge Recovery handwheel angles used in Phases VI and VII are presented in Tables 5.1 and 5.2, respectively. These tables are located at the end of this chapter. Additionally, these tables present the overall range of dwell times observed during tests performed with each vehicle and load configuration.

The nominal maneuver entrance speeds used in the Road Edge Recovery maneuver ranged from 35 to 50 mph, and were increased in 5 mph increments until a termination condition was achieved. Termination conditions included two-wheel lift or completion of a test performed at the maximum maneuver entrance speed without two-wheel lift. If two-wheel lift was observed, a downward iteration of vehicle speed was used in 1 mph increments until lift was no longer detected. Once the lowest speed for which two-wheel lift could be detected was isolated, two additional Road Edge Recovery maneuvers were performed at that speed to monitor two-wheel lift repeatability. These termination conditions may be modified, given the occurrence of tire debeading and/or rim-to-pavement contact. This will be discussed in further detail in Chapter 7.

Table 5.1. Phase VI Rollover Resistance Maneuver Handwheel Angles and Road Edge Recovery Dwell Times.

Vehicle	J-Turn Handwheel Angles (degrees)		Road Edge Recovery			
			Nominal Load		Maximum Occupancy	
	Nominal Load	Maximum Occupancy	Handwheel Angle (degrees)	Dwell Time Range (ms)	Handwheel Angle (degrees)	Dwell Time Range (ms)
1998 Honda CR-V	284	287	230	160 - 220	233	370 - 490
1998 Chevrolet Tracker	316	318	256	120 - 260	258	160 - 230
1997 Jeep Cherokee Sport	368	376	299	105 - 120	306	100 - 180
2001 Toyota 4Runner[1]	362	353	294	30 – 115	287	105 - 150
1996 Acura SLX	360	384	293	145 - 195	312	190 - 250
2001 Ford Explorer XLS	312	313	254	85 - 130	255	115 - 145
2001 Ford Explorer Sport	282	307	229	110 - 145	249	130 - 170
2001 Chevrolet Blazer	384	400	312	0 - 45	325	20 - 100
1995 Mitsubishi Montero	336	336	273	180 - 475	273	270 - 1010
1992 Ford F-150	Test not performed	493	Test not performed		400	60 - 85
1994 Chevrolet C1500	436	433	354	n/a[2]	352	55 - 100
1997 Ford F-150	340	350	276	50 - 80	285	100 - 135
1995 Chevrolet K1500	Test not performed	410	Test not performed		333	n/a[2] - 45
1997 Ford Ranger 4x2	Test not performed	347	Test not performed		282	90 - 125
1997 Ford Ranger 4x4	443	459	360	n/a[2]	Test not performed	
1998 Plymouth Voyager	358	346	291	100 - 125	270	175 - 225
1995 Ford Windstar GL	341	331	277	110 - 250	269	175 - 305
1994 Dodge Caravan	357	337	290	140 - 155	274	210 - 700
1995 Chevrolet Astro	390	388	317	70 - 90	315	145 - 170
1993 Ford Aerostar	452	451	367	n/a[2] - 35	366	45 - 85
2002 Chevrolet Corvette	226	Test not performed	184	90 - 115	Test not performed	
1992 Honda Civic LX	216	213	175	275 - 515	173	480 - 750
1994 Ford Taurus	312	311	254	85 - 215	253	125 - 610
1993 Chevrolet Caprice Classic	424	456	344	35 - 55	370	n/a[2] - 15
1997 Chevrolet Metro	319	311	260	120 - 280	253	160 - 530
1991 Chevrolet Cavalier	362	372	295	45 - 105	302	70 - 365

[1]The electronic stability control (VSC) installed on the model year 2001 4Runner was disabled during all tests performed in Phase VI. Since the only significant difference between model year 2000 and 2001 4Runners is the presence of stability control (not available in 2000, standard equipment in 2001), the performance of the 2001 model with disabled stability control is representative of an otherwise equivalent 2000 model.

[2]Maximum roll angle was achieved before completion of the initial steer.

Table 5.2. Phase VII Rollover Resistance Maneuver Handwheel Angles and Road Edge Recovery Dwell Times.
(All Tests Performed in the Nominal Load Configuration)

Vehicle	J-Turn		Road Edge Recovery		
	Steering Scalar	Handwheel Angle (degrees)	Steering Scalar	Handwheel Angle (degrees)	Dwell Time Range (ms)
1995 Chevrolet Astro	8.0	390	6.5	317	70 - 90
	7.0	341	5.5	268	125 - 140
	6.0	292	4.5	219	170 - 180
	5.0	244	3.5	170	215 - 230
1993 Ford Aerostar	8.0	452	6.5	367	n/a* - 35
	7.0	395	5.5	310	95 - 115
	6.0	338	4.5	254	155
	5.0	282	3.5	Not Performed	
1997 Ford Ranger 4x2	8.0	Not Performed	6.5	Not Performed	
	7.0	298	5.5	234	100 - 125
	6.0	255	4.5	191	155 - 175
	5.0	213	3.5	148	195 - 205
1997 Ford Ranger 4x4	8.0	443	6.5	360	n/a*
	7.0	387	5.5	304	60 - 85
	6.0	332	4.5	249	125
	5.0	Not Performed	3.5	Not Performed	
2001 Ford Explorer 4x2	8.0	282	6.5	229	110 - 145
	9.0	317	7.5	264	85 - 120
	10.0	352	8.5	300	40 - 65

*Maximum roll angle was achieved before completion of the initial steer.

6.0 HANDWHEEL STEERING INPUT ASSESSMENT

This chapter provides an assessment of the steering machine's ability to execute the handwheel angles and rates commanded during Phase VI J-Turn and Road Edge Recovery maneuvers. Most of the handwheel data used in this assessment were collected during tests performed in the Maximum Occupancy configuration. This was because the Road Edge Recovery dwell times observed in this configuration were typically longer than those seen when the same vehicle was tested with the Nominal Load. The longer dwell times increased the likelihood that steady state steering was achieved following completion of the initial steering input. This is important since the steering machine has a small amount of mechanical overshoot after completion of a rapid steering ramp, as shown in Figure 6.1. If a Road Edge Recovery steering reversal is initiated a very short time after completion of the initial steer (i.e., steady state steering is not achieved before the reversal occurs), this overshoot can confound attempts to determine whether the commanded input was actually achieved. Depending on the vehicle being evaluated, overshoot durations generally ranged from approximately 80 to 120 ms.

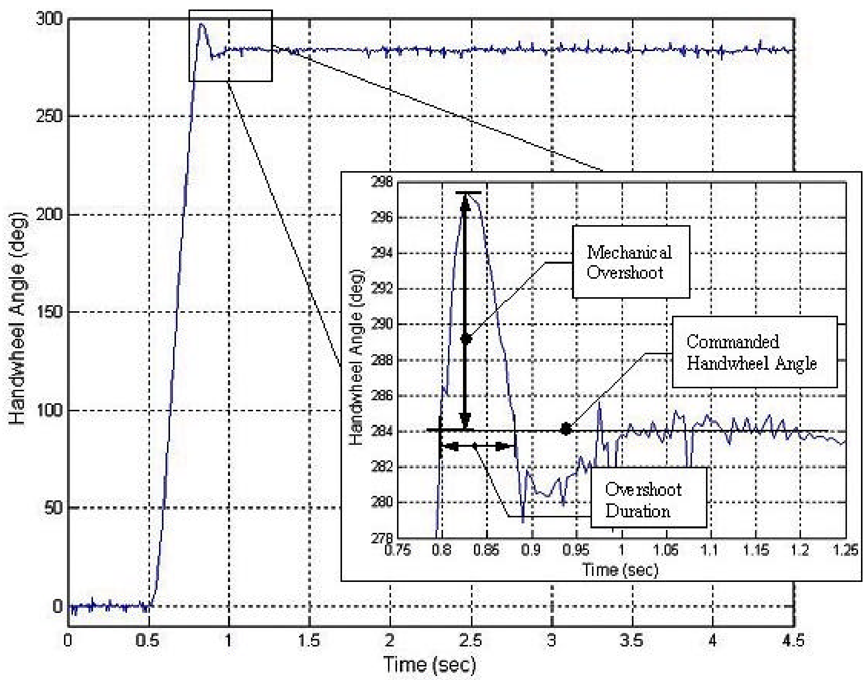


Figure 6.1. Mechanical overshoot of the steering machine recorded during a right-steer J-Turn performed with a 1998 Honda CR-V.

Up to twelve J-Turns and eight Road Edge Recovery maneuvers were considered per vehicle. However, if two-wheel lift or tire debeading occurred, the number of tests available for analysis could be less. All J-Turn and Road Edge Recovery maneuvers were performed with commanded steering rates of 1000 and 720 degrees per second, respectively, regardless of load configuration.

6.1 Achieving Desired Handwheel Angles

For every vehicle considered, J-Turn handwheel angle data were averaged for 1000 ms after the instant the commanded angle was first achieved. The ranges and overall average values are reported on a per-vehicle basis in Table 6.1. The steering machine was able to achieve overall average handwheel angles within ± 10 degrees (± 2.3 percent) of the commanded values. For twenty-five of the twenty-six J-Turn tests considered (96 percent), the steering machine was able to achieve handwheel angles within ± 2.0 percent of the commanded values.

For every vehicle considered, Road Edge Recovery handwheel data were averaged from 80 ms after completion of the initial steer (to minimize the effect of mechanical overshoot) to the initiation of the reversal to determine "Initial Steer Magnitudes." The "Reversal Magnitudes" were determined by averaging the handwheel data for 1000 ms after the instant the commanded angle of the reversal was first achieved. The ranges and overall average values are reported on a per-vehicle basis in Table 6.2. If the dwell time from completion of the initial steer to the initiation of the reversal was less than 80 ms, the Initial Steer Magnitude of that test was not calculated. For this reason, no Initial Steer Magnitudes are given in Table 6.2 for the Chevrolet K1500 and Chevrolet Caprice.

The steering machine was able to achieve overall average initial steer handwheel angles within ± 10 degrees (± 2.7 percent) of the commanded values. For twenty-five of the twenty-six Road Edge Recovery tests considered (96 percent), overall average initial steer handwheel angles were within ± 2.0 percent of the commanded values. The steering machine was able to achieve reversals within ± 5 degrees (± 1.4 percent) of the commanded values for each of the twenty-six vehicles.

Table 6.1. Steering Inputs Used To Examine J-Turn Handwheel Angles (Phase VI).

Vehicle	Commanded (degrees)	Actual (degrees)	
		Range	Overall Average
1998 Honda CR-V	287	287	287
1998 Chevrolet Tracker	318	318 - 320	319
1997 Jeep Cherokee Sport	368	367 - 369	368
2001 Toyota 4Runner*	353	353 - 355	354
1996 Acura SLX	384	384 - 386	385
2001 Ford Explorer XLS	313	314 - 315	314
2001 Ford Explorer Sport	307	307 - 309	308
2001 Chevrolet Blazer	400	400	400
1995 Mitsubishi Montero	336	333 - 334	334
1992 Ford F-150	493	490 - 497	493
1994 Chevrolet C1500	433	442 - 444	443
1997 Ford F-150	350	348 - 350	349
1995 Chevrolet K1500	410	410 - 411	410
1997 Ford Ranger 4x2	347	342 - 343	343
1997 Ford Ranger 4x4	443	442 - 443	442
1998 Plymouth Voyager	346	345 - 346	346
1995 Ford Windstar GL	331	326 - 327	327
1994 Dodge Caravan	337	337 - 339	338
1995 Chevrolet Astro	388	380 - 389	388
1993 Ford Aerostar	451	456 - 458	457
2002 Chevrolet Corvette	226	223 - 226	225
1992 Honda Civic LX	213	210 - 217	213
1994 Ford Taurus	311	308 - 309	308
1993 Chevrolet Caprice Classic	456	449 - 455	453
1997 Chevrolet Metro	311	309 - 310	310
1991 Chevrolet Cavalier	372	369 - 371	370

*The electronic stability control (VSC) installed on the model year 2001 4Runner was disabled during all tests performed in Phase VI. Since the only significant difference between model year 2000 and 2001 4Runners is the presence of stability control (not available in 2000, standard equipment in 2001), the performance of the 2001 model with disabled stability control is representative of an otherwise equivalent 2000 model.

Table 6.2. Steering Inputs Used To Examine Road Edge Recovery Handwheel Angles (Phase VI).

Vehicle	Initial Steer Magnitude			Reversal Magnitude		
	Commanded (degrees)	Actual (degrees)		Commanded (degrees)	Actual (degrees)	
		Range	Overall Average		Range	Overall Average
1998 Honda CR-V	230	228 - 230	229	230	230	230
1998 Chevrolet Tracker	258	256 - 260	258	258	256 - 259	258
1997 Jeep Cherokee Sport	306	305 - 308	306	306	306 - 307	306
2001 Toyota 4Runner[1]	287	283 - 288	287	287	286 - 288	287
1996 Acura SLX	312	310 - 312	311	312	312 - 313	312
2001 Ford Explorer XLS	255	255 - 258	256	255	254 - 255	255
2001 Ford Explorer Sport	249	248 - 251	249	249	249 - 250	250
2001 Chevrolet Blazer	325	323 - 324	323	325	324 - 325	325
1995 Mitsubishi Montero	273	270 - 272	270	273	270 - 273	271
1992 Ford F-150	400	399	399	400	396 - 400	398
1994 Chevrolet C1500	352	357 - 358	358	352	350 - 352	351
1997 Ford F-150	285	284 - 286	285	285	283 - 285	284
1995 Chevrolet K1500	333	n/a[2]	n/a[2]	333	332 - 335	333
1997 Ford Ranger 4x2	282	279 - 281	280	282	278 - 280	279
1997 Ford Ranger 4x4	360	358 - 363	360	360	359 - 362	361
1998 Plymouth Voyager	281	280 - 281	280	281	281 - 282	282
1995 Ford Windstar GL	269	265 - 267	266	269	265 - 267	266
1994 Dodge Caravan	274	273 - 275	274	274	273 - 274	274
1995 Chevrolet Astro	315	313 - 315	314	315	315 - 316	315
1993 Ford Aerostar	366	376 - 377	376	366	369 - 371	370
2002 Chevrolet Corvette	184	180 - 183	181	184	182 - 183	183
1992 Honda Civic LX	173	172 - 175	173	173	169 - 176	173
1994 Ford Taurus	253	248 - 250	249	253	250 - 252	251
1993 Chevrolet Caprice Classic	370	n/a[2]	n/a[2]	370	362 – 367	365
1997 Chevrolet Metro	253	249 – 252	250	253	250 – 253	251
1991 Chevrolet Cavalier	303	299 – 302	300	303	300 – 302	301

[1]The electronic stability control (VSC) installed on the model year 2001 4Runner was disabled during all tests performed in Phase VI. Since the only significant difference between model year 2000 and 2001 4Runners is the presence of stability control (not available in 2000, standard equipment in 2001), the performance of the 2001 model with disabled stability control is representative of an otherwise equivalent 2000 model.

[2]All handwheel dwell times observed during these test series were less than 80 ms. Therefore, it was impossible to distinguish the mechanical overshoot of the steering machine from its intended input.

6.2 Achieving Desired Handwheel Rates

In its response to the October 7, 2002 Notice of Proposed Rulemaking (NPRM) published in the Federal Register, the Alliance of Automobile Manufacturers suggested the commanded handwheel rates used in NHTSA's rollover resistance maneuvers can be so great that flow restrictions in some vehicles' power steering systems may not be able to "keep up" with the steering inputs. The result of this phenomenon is a loss of power assisted steering effectiveness. According to the Alliance, to maintain the commanded handwheel steering rate despite the loss of power assist, the steering torque requirement is increased—a demand some steering machines may not be capable of effectively overcoming. For this reason, the ability of the steering machine to achieve the commanded handwheel rates is of interest to NHTSA.

The torque output from the steering machine used in Phase VI was not measured in Phase VI. However, the ability of the machine to sustain a commanded rate was determined by calculating the slopes of first-order regression lines fitted to the actual handwheel angle data. Although the previous section demonstrated the steering machine was able to repeatably achieve commanded handwheel angles, the machine was often unable to accurately generate the commanded handwheel rates, especially during J-Turn maneuvers performed with certain vehicles.

The steering machine achieved overall average handwheel rates within ± 230 deg/sec (± 23.3 percent) of the commanded value (1000 deg/sec) during the J-Turn maneuver. The actual overall average steering rates for seventeen of the twenty-six vehicles rates were within ± 10.0 percent commanded values. Table 6.3 summarizes results from the J-Turn handwheel steering rate examination. Commanded handwheel rates are compared to those actually measured. The overall coefficients of the regression lines describing the individual left and right steer test data are provided.

When the initial steer handwheel data of the Road Edge Recovery tests were considered, the steering machine was able to achieve overall average handwheel rates within ± 69 deg/sec (± 9.6 percent) of the commanded value (720 deg/sec). The overall average handwheel rates of the steering reversals were within ± 78 deg/sec (± 10.8 percent) of the commanded value (720 deg/sec). For twenty-five of the twenty-six Road Edge Recovery tests considered (96 percent), overall average reversal handwheel rates were within ± 10.0 percent of the commanded values. Table 6.4 summarizes results from Road Edge Recovery handwheel steering rate examination. Commanded handwheel rates are compared to those actually measured. The overall coefficients of the regression lines describing the individual left and right steer test data are provided.

Table 6.3. Steering Inputs Used To Examine J-Turn Handwheel Rates (Phase VI).

Vehicle	Commanded Rate (deg/sec)	Actual Rate (deg/sec)		
		Range	Overall Average	R^2 Range
1998 Honda CR-V	1000	1041 - 1148	1100	0.9990-0.9998
1998 Chevrolet Tracker	1000	1037 - 1067	1054	0.9923-0.9990
1997 Jeep Cherokee Sport	1000	889 - 1044	976	0.9928-0.9977
2001 Toyota 4Runner*	1000	1016 - 1034	1023	0.9984-0.9998
1996 Acura SLX	1000	1114 - 1146	1126	0.9947-0.9982
2001 Ford Explorer XLS	1000	1042 - 1057	1047	0.9970-0.9985
2001 Ford Explorer Sport	1000	1161 - 1184	1177	0.9957-0.9974
2001 Chevrolet Blazer	1000	976 - 1040	1023	0.9968-0.9987
1995 Mitsubishi Montero	1000	947 - 1030	1013	0.9968-0.9986
1992 Ford F-150	1000	741 - 795	770	0.9905-0.9946
1994 Chevrolet C1500	1000	989 - 1079	1040	0.9961-0.9984
1997 Ford F-150	1000	732 - 831	777	0.9939-0.9965
1995 Chevrolet K1500	1000	1013 - 1050	1034	0.9963-0.9981
1997 Ford Ranger 4x2	1000	940 - 1011	983	0.9975-0.9989
1997 Ford Ranger 4x4	1000	802 - 863	845	0.9870-0.9937
1998 Plymouth Voyager	1000	931 - 1053	995	0.9887-0.9967
1995 Ford Windstar GL	1000	874 - 998	940	0.9941-0.9989
1994 Dodge Caravan	1000	1034 - 1059	1047	0.9984-0.9991
1995 Chevrolet Astro	1000	969 - 1069	1038	0.9973-0.9976
1993 Ford Aerostar	1000	1116 - 1135	1126	0.9951-0.9962
2002 Chevrolet Corvette	1000	1060 - 1159	1104	0.9961-0.9991
1992 Honda Civic LX	1000	1048 - 1123	1093	0.9863-0.9960
1994 Ford Taurus	1000	1084 - 1149	1122	0.9984-0.997
1993 Chevrolet Caprice Classic	1000	958 - 1015	991	0.9990-0.9996
1997 Chevrolet Metro	1000	1113 - 1161	1136	0.9924-0.9958
1991 Chevrolet Cavalier	1000	1002 - 1029	1014	0.9976-0.9993

*The electronic stability control (VSC) installed on the model year 2001 4Runner was disabled during all tests performed in Phase VI. Since the only significant difference between model year 2000 and 2001 4Runners is the presence of stability control (not available in 2000, standard equipment in 2001), the performance of the 2001 model with disabled stability control is representative of an otherwise equivalent 2000 model.

Table 6.4. Steering Inputs Used To Examine Road Edge Recovery Handwheel Rates (Phase VI).

Vehicle	Initial Steer Magnitude (deg/sec)				Reversal Magnitude (deg/sec)			
	Commanded	Actual			Commanded	Actual		
		Range	Overall Average	R^2 Range		Range	Overall Average	R^2 Range
1998 Honda CR-V	720	747-763	755	0.9967 - 0.9980	720	713-725	719	0.9991 - 0.9995
1998 Chevrolet Tracker	720	722-754	730	0.9843 - 0.9993	720	714-727	722	0.9980 - 0.9993
1997 Jeep Cherokee Sport	720	736-748	742	0.9989 - 0.9993	720	666-718	706	0.9934 - 0.9998
2001 Toyota 4Runner*	720	721-739	731	0.9987 - 0.9997	720	708-723	718	0.9996 - 0.9999
1996 Acura SLX	720	739-754	745	0.9963 - 0.9984	720	707-721	714	0.9990 - 0.9997
2001 Ford Explorer XLS	720	729-742	737	0.9924 - 0.9980	720	716-724	721	0.9988 - 0.9995
2001 Ford Explorer Sport	720	761-773	768	0.9952 - 0.9963	720	715-723	718	0.9991 - 0.9996
2001 Chevrolet Blazer	720	728-732	730	0.9990 - 0.9995	720	715-716	716	0.9999 - 1.0000
1995 Mitsubishi Montero	720	712-733	722	0.9959 - 0.9976	720	713-721	717	0.9993 - 0.9960
1992 Ford F-150	720	719-726	723	0.9992 - 0.9997	720	619-715	658	0.9745 - 0.9999
1994 Chevrolet C1500	720	734-742	739	0.9976 - 0.9990	720	709-716	714	0.9998 - 0.9999
1997 Ford F-150	720	713-735	724	0.9941 - 0.9997	720	698-720	711	0.9975 - 0.9996
1995 Chevrolet K1500	720	735-740	737	0.9980 - 0.9988	720	650-717	701	0.9898 - 0.9999
1997 Ford Ranger 4x2	720	712-736	722	0.9965 - 0.9983	720	705-712	710	0.9992 - 0.9996
1997 Ford Ranger 4x4	720	733-744	738	0.9977 - 0.9994	720	597-692	642	0.9743 - 0.9980
1998 Plymouth Voyager	720	747-766	757	0.9958 - 0.9973	720	717-722	719	0.9991 - 0.9997
1995 Ford Windstar GL	720	702-715	708	0.9980 - 0.9986	720	687-711	704	0.9969 - 0.9996
1994 Dodge Caravan	720	723-737	732	0.9977 - 0.9993	720	720-726	722	0.9994 - 0.9998
1995 Chevrolet Astro	720	731-743	737	0.9985 - 0.9992	720	716-718	717	0.9998 - 0.9999
1993 Ford Aerostar	720	745-752	749	0.9973 - 0.9980	720	590-722	678	0.9644 - 0.9999
2002 Chevrolet Corvette	720	782-796	789	0.9936 - 0.9972	720	649-709	694	0.9935 - 0.9991
1992 Honda Civic LX	720	732-767	747	0.9452 -0.9980	720	723-743	733	0.9940 - 0.9986
1994 Ford Taurus	720	740-765	753	0.9966 - 0.9981	720	566-710	669	0.9459 - 0.9997
1993 Chevrolet Caprice Classic	720	712-729	721	0.9990 - 0.9993	720	688-707	701	0.9957 - 0.9997
1997 Chevrolet Metro	720	726-747	738	0.9950 - 0.9970	720	710-732	717	0.9968 - 0.9997
1991 Chevrolet Cavalier	720	683-728	715	0.9858 - 0.9976	720	709-716	713	0.9988 - 0.9996

*The electronic stability control (VSC) installed on the model year 2001 4Runner was disabled during all tests performed in Phase VI. Since the only significant difference between model year 2000 and 2001 4Runners is the presence of stability control (not available in 2000, standard equipment in 2001), the performance of the 2001 model with disabled stability control is representative of an otherwise equivalent 2000 model.

So why was the steering machine unable to achieve the commanded handwheel rates with the accuracy it could achieve the commanded angles? This is best explained by considering two factors: the manner in which the machine interprets the commands specified by the experimenter, and the nonlinearity of the steering inputs used for some vehicles. These factors are discussed in the next two sections.

6.2.1 Interpretation of Commanded Steering Inputs

When an experimenter writes the code used to define steering inputs, only handwheel position and instants in the time domain are specified. The experimenter does not have the option of explicitly programming handwheel steering rate. The steering machine uses a position control feedback loop to monitor handwheel steering angle and time. This allows the torque input by the machine to be modulated in a way that best allows the commanded angles to be achieved in the specified amount of time. Since the code used to command J-Turn and Road Edge Recovery handwheel inputs is made up of simple ramp functions (e.g., "ramp to ***d*** degrees in *t* seconds), the steering machine's feedback loop may require the steering rate to be increased to overcome transients at the initiation of steer. This is done to insure the actual handwheel ramps are completed at the user-specified instants in time. In other words, the actual rates applied by the steering machine are not simply defined as ***d/t***.

6.2.2 Discussion of Steering Divergence

In Phase IV, unintentional "jogs" were detected in the handwheel angle data traces recorded during some Nissan Fishhook tests [1]. Although the cause of this phenomenon was not isolated, NHTSA researchers speculated the steering machine's 60-volt power supply was in suspect. The presence of the divergence was not believed to adversely affect maneuver severity.

In Phase VI, similar divergences were observed during J-Turn and Road Edge Recovery tests performed with some vehicles. An example of this phenomenon, observed during a right-steer J-Turn performed with a 1992 Ford F-150, is shown in Figure 6.2. When divergence occurred, the method used to determine how successful the steering machine was able to achieve the commanded handwheel rates (as explained at the beginning of this chapter) did not effectively report the controller's ability. This is because these divergences reduce the linearity of the handwheel inputs, and the analysis method used to calculate steering rate relies on accurate first-order representation. To accommodate the steering divergences, the slopes of the respective regression lines were lessened. This caused much of the actual steering rate input to be underrepresented.

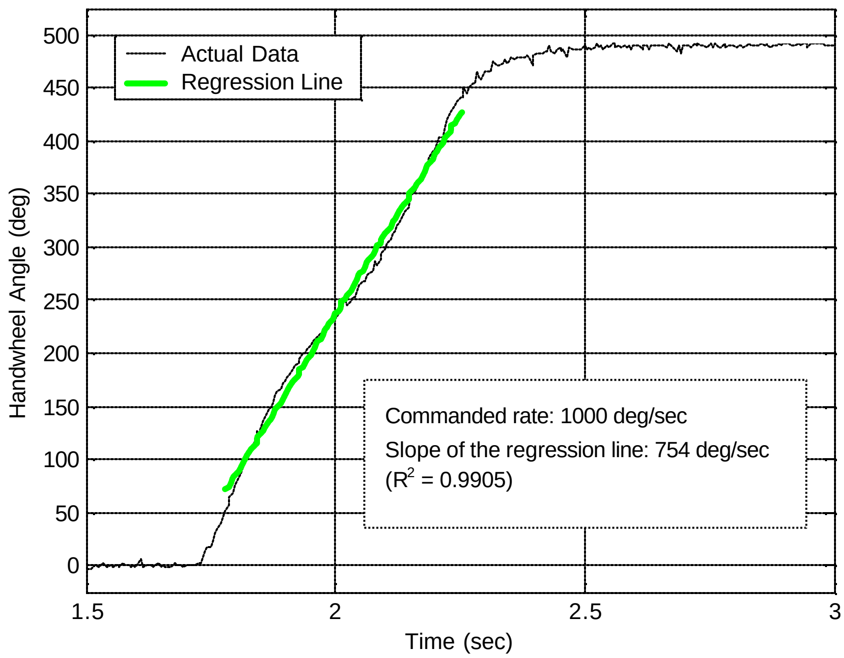


Figure 6.2. Right-steer J-Turn handwheel input fitted with a best-fit regression line. The test was performed with a 1992 Ford F-150.

Now consider the data presented in Figure 6.3. In this figure, two regression lines have been fitted to the same handwheel angle trace presented previously in Figure 6.2. The first line spans from shortly after the handwheel input was initiated to the point where steering divergence began. The second line begins just after the divergence ended to just before completion of the steering ramp. The slopes of the first and second lines were 1119 and 963 deg/sec, respectively. Therefore, despite the steering divergence seen in this example, the steering machine was able to successfully execute the commanded steering input for a majority of the maneuver. In the example presented in Figures 6.2 and 6.3, the duration of the steering divergence was approximately 230 ms, 46 percent of the total commanded duration of 493 ms[8]. Therefore, rates similar to the commanded values were achieved during 54 percent of the maneuver.

[8] J-Turn tests performed with the 1992 Ford F150 used a commanded handwheel steering angle of 493 degrees in the Maximum Occupancy configuration. Input at 1000 deg/sec, this should take 493 ms to complete.

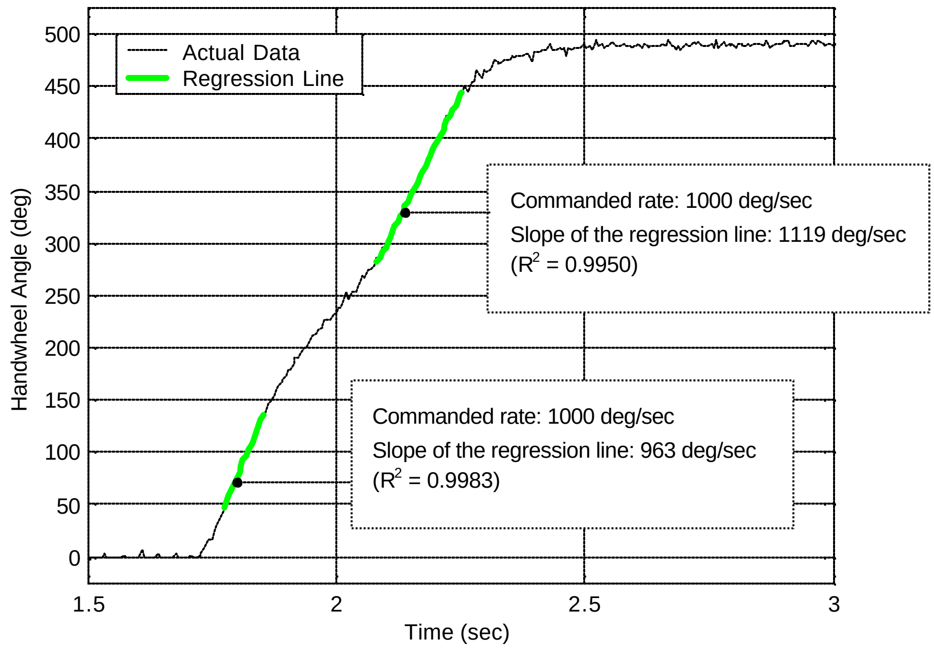


Figure 6.3. Right-steer J-Turn handwheel input fitted with pre- and post-steering divergence regression lines. The test was performed with a 1992 Ford F-150.

Handwheel steering divergence was observed during J-Turns performed with four vehicles. Despite the lower handwheel rates, the phenomenon occurred during Road Edge Recovery maneuvers performed with seven vehicles. Table 6.5 summarizes six aspects pertaining to J-Turn steering divergence including: Time and Steering Rate Up To Divergence, Steering Angle At Divergence, Time To Divergence Recovery, Steering Rate After Divergence, and Steering Angle At Divergence Recovery. Table 6.6 summarizes the data relating to Road Edge Recovery maneuvers. In the case of the Road Edge Recovery maneuver, steering divergence was never observed during the initial steer; it always occurred during the reversal phase of the maneuver. Note that although steering divergence occurred in a majority of the tests for the vehicles featured in Tables 6.5 and 6.6, it did not necessarily occur for every one. The data presented in these tables summarize results only from the tests an obvious divergence was observed.

Table 6.5. Vehicles With Steering Divergence Observed During J-Turn Testing (Phase VI).

Vehicle	Time To Divergence (ms)		Steering Rate Up To Divergence (deg/sec)		Steering Angle At Divergence (degrees)		Time To Divergence Recovery (ms)		Steering Rate After Divergence (deg/sec)		Steering Angle At Divergence Recovery (degrees)	
	Range	Average	Range	Average	Range	Average	Range	Average	Range	Average	Range	Average
1997 Jeep Cherokee Sport	140 - 175	155	1077 - 1176	1135	130 - 161	144	75 - 145	106	1034 - 1336	1209	201 - 257	233
1992 Ford F-150	110 - 200	157	983 - 1190	1084	108 - 186	153	185 - 250	228	901 - 995	954	270 - 337	309
1997 Ford F-150	90 - 150	126	959 - 1075	1022	72 - 131	115	40 - 120	81	763 - 904	843	135 - 191	169
1997 Ford Ranger 4x4	145 - 185	164	1048 - 1160	1112	130 - 167	148	105 - 150	132	965 - 1118	1035	207 - 264	234

Table 6.6. Vehicles With Steering Divergence Observed During Road Edge Recovery Testing (Phase VI).

Vehicle	Time To Divergence (ms)		Steering Rate Up To Divergence (deg/sec)		Steering Angle At Divergence (degrees)		Time To Divergence Recovery (ms)		Steering Rate After Divergence (deg/sec)		Steering Angle At Divergence Recovery (degrees)	
	Range	Average	Range	Average	Range	Average	Range	Average	Range	Average	Range	Average
1997 Jeep Cherokee Sport	1250[1]	1250[1]	743[1]	743[1]	191[1]	191[1]	160[1]	160[1]	n/a[2]	n/a[2]	255[1]	255[1]
1992 Ford F-150	1480 - 1715	1621	705 - 723	714	191 - 376	292	145 - 280	206	n/a[2]	n/a[2]	303 - 388	339
1995 Chevrolet K1500	1115 - 1210	1163	720 - 727	724	112 - 187	149	140 - 155	148	n/a[2]	n/a[2]	195 - 232	214
1997 Ford Ranger 4x4	1185 - 1495	1306	717 - 746	732	129 - 230	230	105 - 235	176	n/a[2]	n/a[2]	181 - 360	249
1993 Ford Aerostar	1435 - 1560	1499	716 - 723	720	252 - 327	286	70 - 220	140	n/a[2]	n/a[2]	268 - 365	314
1994 Ford Taurus	1100 - 1180	1138	704 - 714	708	168 - 219	197	105 - 205	135	n/a[2]	n/a[2]	206 - 230	217
1993 Chevrolet Caprice Classic	1290 - 1375	1335	721 -726	724	191 - 237	205	85 - 150	125	n/a[2]	n/a[2]	247 - 301	267

[1]Only one test contained a steering divergence.

[2]Insufficient steering angle data for a post-divergence regression line, therefore the rate cannot be accurately determined.

Perusal of the divergence durations seen for each vehicle indicates that when steering divergence occurs, a loss of the commanded handwheel rate lasted 40 to 250 ms during J-Turns and 70 to 280 ms during Road Edge Recovery maneuvers. Consideration of lateral acceleration, roll rate, and roll angle data indicate vehicles are capable of responding to steering divergences present during the conduct of these maneuvers, as shown in Figures 6.4 through 6.7. However, the extent to which a vehicle is able to respond to such divergence depends on a number of factors: the vehicle, maneuver, steering angle, and whether the lateral capability of the tires has been exceeded.

In the case of the J-Turn (Figures 6.4 and 6.5), lateral acceleration was reduced during the steering divergence. Note that the lateral acceleration to handwheel angle gain did not recover to the level present before the steering divergence in either example. This was because the steering divergences ended after the lateral accelerations had become non-linear (after about 0.4 g), and the non-linear lateral acceleration to handwheel angle gain was less than that of the linear response gain. Yaw and roll responses were not obviously affected by the presence of the steering divergences seen in Figures 6.4 and 6.5.

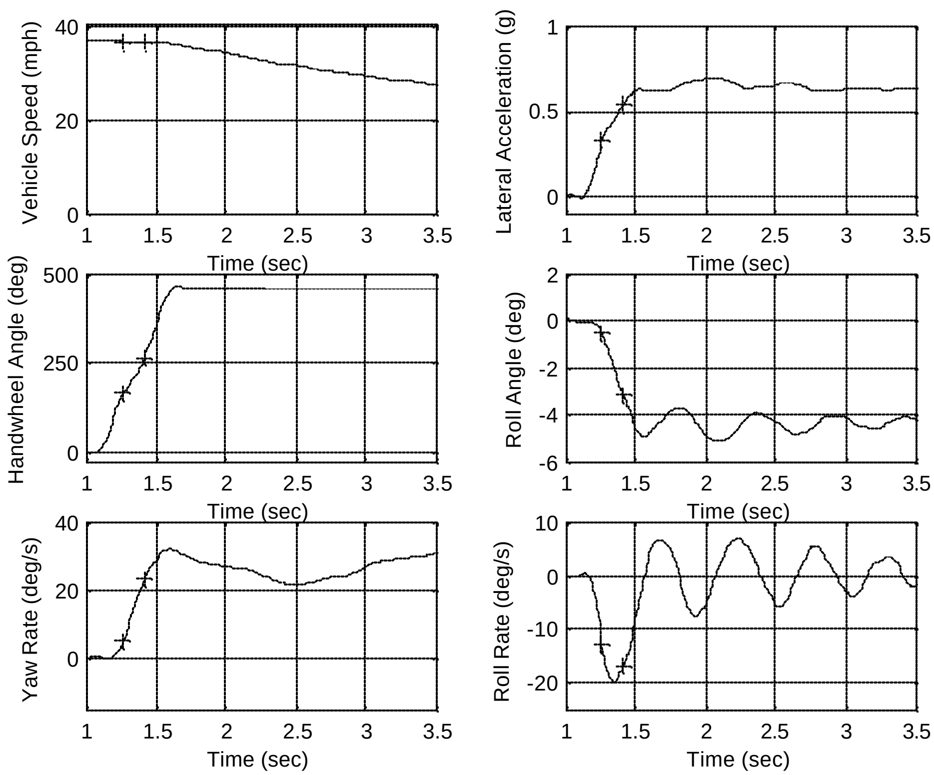


Figure 6.4. Right-steer J-Turn performed with a 1997 Ford Ranger 4x4 at 36.8 mph. The times corresponding to beginning and end of the handwheel steering divergence are indicated in each pane.

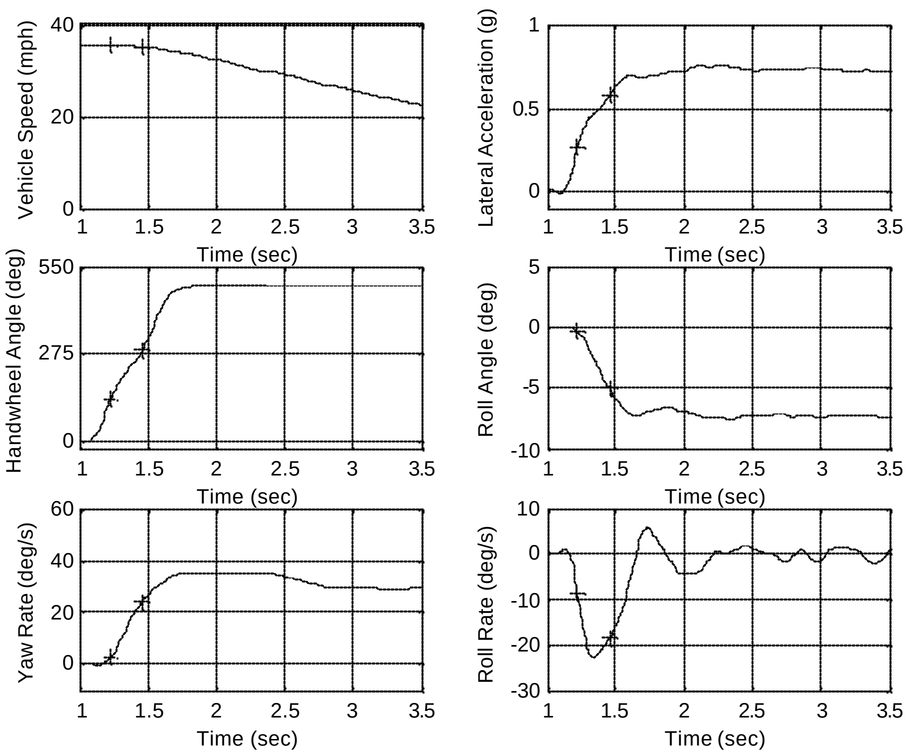


Figure 6.5. Right-steer J-Turn performed with a 1992 Ford F150 at 35.7 mph. The times corresponding to beginning and end of the handwheel steering divergence are indicated in each pane.

The steering divergences present during Road Edge Recovery tests (Figures 6.6 and 6.7) occurred during the reversal phase of the maneuvers. In the case of Figure 6.6, the effect of the steering divergence was seen in the lateral acceleration data. That said, the vehicle was able to smoothly generate lateral acceleration from the end of the steering divergence to the first local lateral acceleration peak. Although a dip in the roll rate magnitude occurred between 2.3 and 2.6 seconds after initiation of the steering input, it began prior to the steering divergence. Peak roll rate coincided with the completion of the steering reversal. Realizing this, it appears the steering divergence had little to no effect on the roll rate observed during this maneuver. Yaw and roll angle responses were not noticeably affected by the presence of the steering divergences seen in Figures 6.6.

Figure 6.7 presents data collected during three Road Edge Recovery tests performed in sequence. Steering divergences occurred near the completion of each handwheel reversal. The effect of the steering divergences was not obvious in any of the data presented in Figure 6.7, regardless of the divergence magnitude. In this example, differences in the way the vehicle responded to the three steering inputs are best explained by the realizing the range of the corresponding maneuver entrance speeds. Tests 0406 and 0407 began within 1.3 mph of each other. As such, the data produced by these tests were nearly identical. The maneuver entrance speed of Test 0405 was lower than either Test 0406 or 0407 (by up to 5.1 mph). These differences in entrance speed explain why the vehicle responses of Test 0405 differ slightly from the others presented in Figure 6.7.

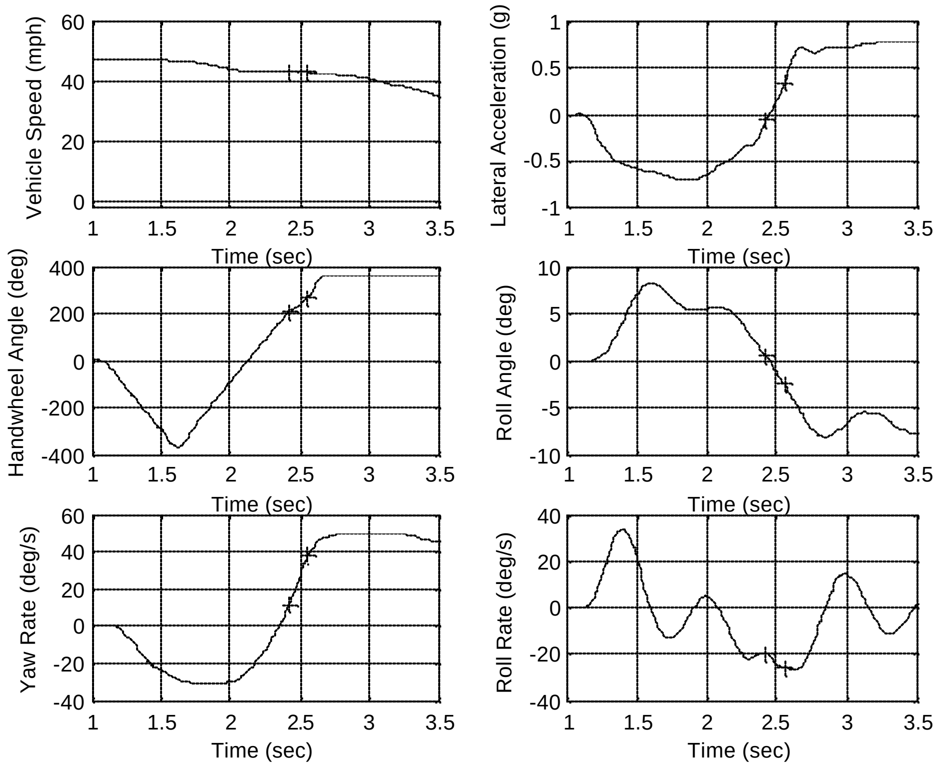


Figure 6.6. Left-right Road Edge Recovery maneuver performed with a 1993 Chevrolet Caprice at 47.0 mph. The times corresponding to beginning and end of the handwheel steering divergence are indicated in each pane.

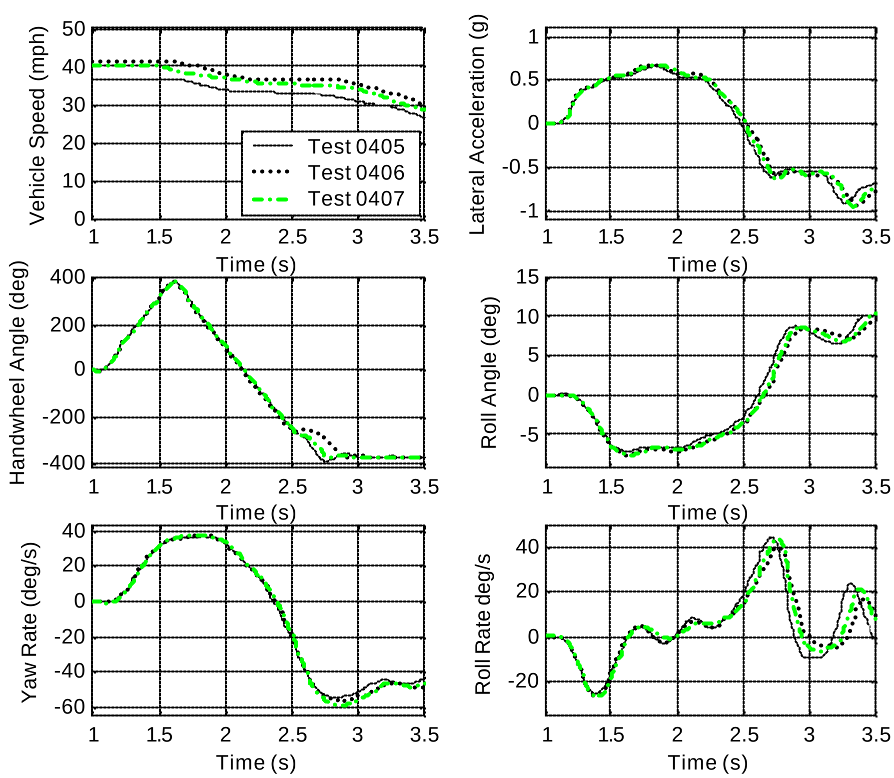


Figure 6.7. Right-left Road Edge Recovery maneuvers performed with a 1993 Ford Aerostar at 36.6, 41.7, and 40.4 mph.

The results discussed in this section seem to support the Alliance of Automobile Manufacturers' suggestion that it is possible for the commanded handwheel rates used in NHTSA's rollover resistance maneuvers to be so great that flow restrictions in some vehicles' power steering systems may not be able to "keep up" with the steering input. If the increased steering torque resulting from a loss of power assist is responsible for the steering divergence seen in Phase VI, VRTC's steering machine may not be capable of overcoming the steering burden imposed by all light vehicles. Regrettably, neither handwheel torque nor the status of the steering machine's supply voltage were recorded during Phase VI testing.

That said, the overall rates output by the linear approximations given in Tables 6.3 and 6.4 indicate the steering machine was usually able to produce the commanded steering rates for the commanded period of time. In the instances where a steering divergence was seen, the pre- and post divergence handwheel rates were generally quite close to the commanded steering rates. Although it is believed that vehicles being subjected to J-Turn and Road Edge Recovery maneuvers are capable of responding to the steering divergences that can occur in these maneuvers, the authors continue to believe these divergences do not compromise maneuver severity or two-wheel lift repeatability. Furthermore, the authors believe the maximum torque capacity of the steering machine (36.9 lbf-ft) is able to adequately execute J-Turn or Road Edge Recovery maneuvers, and that modifications to the steering machine (to increase the maximum torque capacity) are not necessary.

7.0 ROLLOVER RESISTANCE MANEUVER TEST RESULTS

In this chapter, tests results from both Phase VI and Phase VII are presented. When considering these results, it is important for the reader to recall that Phase VII was primarily concerned with addressing some of the issues that became apparent during the Phase VI of the program.

7.1 Phase VI Test Results

This section presents a summary of the two-wheel lifts, instances of rim-to-pavement contact, and tire debeading observed during Phase VI testing. Discussions of how rim-to-pavement contact and tire debeading affected the way the test procedure was executed, and an explanation of why some tests were terminated early, or not performed, are also provided.

7.1.1 Two -Wheel Lift

Two-wheel lift was defined as the occurrence of at least two inches of simultaneous lift of the inside wheels from the test surface. Two-wheel lift less than two inches was not considered. Furthermore, two-wheel lift great enough to require outriggers to suppress roll motion was reported simply as "two-wheel lift" as long as at least two inches of simultaneous two-wheel lift occurred before outrigger contact with the ground was made.

Of the twenty-six vehicles evaluated in Phase VI, ten produced two-wheel lift. The only vehicle for which two-wheel lift was observed during each of the four Rollover Resistance Maneuver / load configuration combinations was the Acura SLX. The SSFs of the SLX in the Nominal Load and Maximum Occupancy load configurations were 1.128 and 1.081, respectively.

The most common tip-up scenario (for five of the ten vehicles: the Honda CR-V, Chevrolet Blazer, Mitsubishi Montero, Ford Ranger 4x4, and Ford Aerostar) was lift during the Maximum Occupancy J-Turn, Nominal Load Road Edge Recovery, and Maximum Occupancy Road Edge Recovery maneuvers. The SSFs of these vehicles ranged from 0.980 to 1.234 in the Nominal Load configuration and from 0.946 to 1.213 at Maximum Occupancy.

Three vehicles–the Chevrolet Tracker, Ford Explorer XLS, and Toyota 4Runner–only experienced two-wheel lift during Road Edge Recovery tests performed in the Maximum Occupancy configuration. The SSFs of these vehicles ranged from 1.079 to 1.105 at Maximum Occupancy.

The Chevrolet Astro was the only vehicle that experienced two-wheel lift during J-Turn and Road Edge Recovery tests performed in the Maximum Occupancy configuration only (i.e., no tip up occurred during tests performed with Nominal Load). The SSFs of the Astro in the Nominal Load and Maximum Occupancy load configurations were 1.147 and 1.070, respectively.

Tables 7.1 and 7.2 present the minimum maneuver entrance speeds required to produce two-wheel lift and the maneuver entrance speeds for which two-wheel lift first occurred, respectively.

Table 7.1. Minimum Maneuver Entrance Speeds (in mph) For Which Two -Wheel Lift Was Produced During Phase VI. (Sorted By Baseline SSF In Descending Order, Per Vehicle Class).

Vehicle	J-Turn				Road Edge Recovery			
	Nominal Load		Maximum Occupancy		Nominal Load		Maximum Occupancy	
	Left Steer	Right Steer	Left Steer	Right Steer	Left-Right Steering	Right-Left Steering	Left-Right Steering	Right-Left Steering
1998 Honda CR-V	--	--	55.2 (early termination)	-- (early termination)	42.4	-- (early termination)	43.7 (early termination)	Test not performed
1998 Chevrolet Tracker	--	--	--	--	--	--	43.5	45.4
1997 Jeep Cherokee Sport	--	--	--	--	--	--	--	--
2001 Toyota 4Runner*	--	--	--	--	--	--	37.2	45.7
1996 Acura SLX	39.9	50.2	34.6	--	39.5	36.4	35.3	35.9
2001 Ford Explorer XLS	--	--	--	--	--	--	37.5	--
2001 Ford Explorer Sport	--	--	--	--	--	--	--	--
2001 Chevrolet Blazer	--	--	52.4	49.0	40.4	39.6	34.9	34.3
1995 Mitsubishi Montero	--	--	--	30.6	32.7	40.6	34.0	29.7
1992 Ford F-150	Test not performed		--	--	Test not performed		--	--
1994 Chevrolet C1500	--	--	--	--	--	--	--	--
1997 Ford F-150	--	--	--	--	--	--	--	--
1995 Chevrolet K1500	Test not performed				Test not performed		--	--
1997 Ford Ranger 4x2	Test not performed		--	--	Test not performed		--	--
1997 Ford Ranger 4x4	--	--	--	60.9 (early termination)	48.8	51.4 (early termination)	Test not performed	
1998 Plymouth Voyager	--	--	--	--	--	--	--	--
1995 Ford Windstar GL	--	--	--	--	--	--	--	--
1994 Dodge Caravan	--	--	--	--	--	--	--	--
1995 Chevrolet Astro	--	--	--	57.9 (early termination)	--	--	34.5	36.2
1993 Ford Aerostar	--	--	52.1	--	43.3	46.5	46.5	40.8
2002 Chevrolet Corvette	--	--	Test not performed		--	--	Test not performed	
1992 Honda Civic LX	--	--	--	--	--	--	--	--
1994 Ford Taurus	--	--	--	--	--	--	--	--
1993 Chevrolet Caprice Classic	--	--	--	--	--	--	--	--
1997 Chevrolet Metro	--	--	--	--	--	--	--	--
1991 Chevrolet Cavalier	--	--	--	--	--	--	--	--

*The electronic stability control (VSC) installed on the model year 2001 4Runner was disabled during all tests performed in Phase VI. Since the only significant difference between model year 2000 and 2001 4Runners is the presence of stability control (not available in 2000, standard equipment in 2001), the performance of the 2001 model with disabled stability control is representative of an otherwise equivalent 2000 model.

Table 7.2. Maneuver Entrance Speeds (in mph) For Which Two-Wheel Lift Was First Produced During Phase VI (Sorted By Baseline SSF In Descending Order, Per Vehicle Class).

Vehicle	J-Turn				Road Edge Recovery			
	Nominal Load		Maximum Occupancy		Nominal Load		Maximum Occupancy	
	Left Steer	Right Steer	Left Steer	Right Steer	Left-Right Steering	Right-Left Steering	Left-Right Steering	Right-Left Steering
1998 Honda CR-V	--	--	55.2 (early termination)	-- (early termination)	45.9	-- (early termination)	43.7	Test not performed
1998 Chevrolet Tracker	--	--	--	--	--	--	44.9	49.9
1997 Jeep Cherokee Sport	--	--	--	--	--	--	--	--
2001 Toyota 4Runner[1]	--	--	--	--	--	--	40.5	46.7
1996 Acura SLX	47.1	50.7	41.0	--	41.4	36.4	42.1	35.9
2001 Ford Explorer XLS	--	--	--	--	--	--	48.4	--
2001 Ford Explorer Sport	--	--	--	--	--	--	--	--
2001 Chevrolet Blazer	--	--	53.9	49.0	44.8	39.8	39.4	35.2
1995 Mitsubishi Montero	--	--	--	35.6	35.1	45.5	35.5	36.0
1992 Ford F-150	Test not performed		--	--	Test not performed		--	--
1994 Chevrolet C1500	--	--	--	--	--	--	--	--
1997 Ford F-150	--	--	--	--	--	--	--	--
1995 Chevrolet K1500	Test not performed		--	--	Test not performed		--	--
1997 Ford Ranger 4x2	Test not performed		--	--	Test not performed		--	--
1997 Ford Ranger 4x4	--	--	--	60.9	51.2	51.4	Test not performed[2]	
1998 Plymouth Voyager	--	--	--	--	--	--	--	--
1995 Ford Windstar GL	--	--	--	--	--	--	--	--
1994 Dodge Caravan	--	--	--	--	--	--	--	--
1995 Chevrolet Astro	--	--	--	61.4	--	--	36.4	36.2
1993 Ford Aerostar	--	--	56.5	--	46.9	46.5	47.2	41.7
2002 Chevrolet Corvette	--	--	Test not performed		--	--	Test not performed	
1992 Honda Civic LX	--	--	--	--	--	--	--	--
1994 Ford Taurus	--	--	--	--	--	--	--	--
1993 Chevrolet Caprice Classic	--	--	--	--	--	--	--	--
1997 Chevrolet Metro	--	--	--	--	--	--	--	--
1991 Chevrolet Cavalier	--	--	--	--	--	--	--	--

[1]The electronic stability control (VSC) installed on the model year 2001 4Runner was disabled during all tests performed in Phase VI. Since the only significant difference between model year 2000 and 2001 4Runners is the presence of stability control (not available in 2000, standard equipment in 2001), the performance of the 2001 model with disabled stability control is representative of an otherwise equivalent 2000 model.

[2]Although no Road Edge Recovery tests were performed at Maximum Occupancy with the Ranger 4x4, the vehicle did tip up in the Nominal Load configuration. For this reason, the authors are certain two-wheel lift would have occurred at Maximum Occupancy.

7.1.2 Rim-to-Pavement Contact and Tire Debeading

There were ten instances of pavement-to-rim contact observed during Phase VI, four of which resulted in debeading of the tire from the rim. In three of the four debeads, inner tubes were installed at the affected corner of the vehicle. Table 7.3 summarizes the rim-to-pavement contact and tire debeading observed in Phase VI.

Rim-to-pavement contact not producing debeading affected four vehicles. In the case of the Honda CR-V, it was observed twice: during a left steer Maximum Occupancy J-Turn performed at 55.2 mph, and during a left-right Nominal Load Road Edge Recovery performed at 45.9 mph. Rim-to-pavement occurred once with the Ford Ranger 4x4 and Chevrolet Astro: during a right steer J-Turn performed at 60.9 mph, and during a right-left Maximum Occupancy Road Edge Recovery test begun at 36.8 mph, respectively. Like the CR-V, two instances were observed during tests performed with the Dodge Caravan: during a left-right Maximum Occupancy Road Edge Recovery performed at 45.6 mph, and during a right-left Maximum Occupancy Road Edge Recovery begun at 49.6 mph.

Some vehicles for which rim-to-pavement contact was observed also experienced tire debeading. These three vehicles were: the Honda CR-V, Ford Ranger 4x4, and Dodge Caravan. The Road Edge Recovery tests performed with the CR-V resulted in two tire debeads. In the Nominal Load configuration, right-left steering during a test begun at 45.4 mph produced a right front debead. A left front debead was observed during a left-right Maximum Occupancy test performed at 43.7 mph. Both CR-V debeads occurred despite the use of inner tubes. The Ford Ranger 4x4 and Dodge Caravan each had one tire debead. In the case of the Ranger 4x4, a right front debead occurred during a right-left Road Edge Recovery performed with a 51.4 mph entry speed in the Nominal Load configuration. Like the CR-V, this debead occurred despite the use of an inner tube at the affected corner of the vehicle. The Dodge Caravan was the only vehicle to experience a debead induced by a J-Turn; this occurred during a test performed with a 59.7 mph entrance speed in the Maximum Occupancy configuration.

Nine Phase VI vehicles were evaluated in the J-Turn maneuver without inner tubes. Of these nine, only the Dodge Caravan experience a debead.

Table 7.3 summarizes the rim-to-pavement contact and tire debeading observed in this study.

Table 7.3. Maneuver Entrance Speeds (in mph) For Which Tire Debeading and Rim-to-Pavement Contact Occurred During Phase VI (Sorted By Baseline SSF In Descending Order, Per Vehicle Class).

Vehicle	J-Turn				Road Edge Recovery			
	Nominal Load		Maximum Occupancy		Nominal Load		Maximum Occupancy	
	Left Steer	Right Steer	Left Steer	Right Steer	Left-Right Steering	Right-Left Steering	Left-Right Steering	Right-Left Steering
1998 Honda CR-V	--	--	55.2 (RF rim contact)	-- (early termination)	45.9 (LF rim contact)	45.4 (RF debead)	43.7 (LF debead)	Test not performed
1998 Chevrolet Tracker	--	--	--	--	--	--	--	--
1997 Jeep Cherokee Sport	--	--	--	--	--	--	--	--
2001 Toyota 4Runner[1]	--	--	--	--	--	--	--	--
1996 Acura SLX	--	--	--	--	--	--	--	--
2001 Ford Explorer XLS	--	--	--	--	--	--	--	--
2001 Ford Explorer Sport	--	--	--	--	--	--	--	--
2001 Chevrolet Blazer	--	--	--	--	--	--	--	--
1995 Mitsubishi Montero	--	--	--	--	--	--	--	--
1992 Ford F-150	Test not performed		--	--	Test not performed		--	--
1994 Chevrolet C1500	--	--	--	--	--	--	--	--
1997 Ford F-150	--	--	--	--	--	--	--	--
1995 Chevrolet K1500	Test not performed		--	--	Test not performed		--	--
1997 Ford Ranger 4x2	Test not performed		--	58.7 (LF rim contact)	Test not performed		--	--
1997 Ford Ranger 4x4	--	--	--	60.9 (LF rim contact)	--	51.4 (RF debead)	Test not performed[2]	
1998 Plymouth Voyager	--	--	--	--	--	--	--	--
1995 Ford Windstar GL	--	--	--	--	--	--	--	--
1994 Dodge Caravan	--	--	--	59.7 (LF debead)	--	--	45.6 (LF rim contact)	49.6 (RF rim contact)
1995 Chevrolet Astro	--	--	--	-- (early termination)	--	--	--	36.8 (RR rim contact)
1993 Ford Aerostar	--	--	--	--	--	--	--	--
2002 Chevrolet Corvette	--	--	Test not performed		--	--	Test not performed	
1992 Honda Civic LX	--	--	--	--	--	--	--	--
1994 Ford Taurus	--	--	--	--	--	--	--	--
1993 Chevrolet Caprice Classic	--	--	--	--	--	--	--	--
1997 Chevrolet Metro	--	--	--	--	--	--	--	--
1991 Chevrolet Cavalier	--	--	--	--	--	--	--	--

[1]The electronic stability control (VSC) installed on the model year 2001 4Runner was disabled during all tests performed in Phase VI. Since the only significant difference between model year 2000 and 2001 4Runners is the presence of stability control (not available in 2000, standard equipment in 2001), the performance of the 2001 model with disabled stability control is representative of an otherwise equivalent 2000 model.

[2]Although no Road Edge Recovery tests were performed at Maximum Occupancy with the Ranger 4x4, the vehicle did tip up in the Nominal Load configuration. For this reason, the authors are certain two-wheel lift would have occurred at Maximum Occupancy.

7.1.3 How Rim-to-Pavement Contact and Tire Debeading Affected the Test Procedure

NHTSA has demonstrated tire debeading can cause substantial damage to the test surface [1], and that vehicles prone to rim-to-pavement contact (which generally causes minor pavement damage) are also capable to producing tire debeading (which can cause moderate to severe pavement damage). Any kind of marring of the test surface is undesirable to both NHTSA and the owner of the test facility, as NHTSA requires its dynamic rollover resistance tests be performed on a smooth, uniform surfaces. Aside from the financial and logistical repercussions imposed by these events, the potential of the damaged surface (or repaired surface) effecting the outcome exists.

For these reasons, any occurrence of rim-to-pavement contact is of great concern to NHTSA. How these events should be accommodated in the test procedure was not fully resolved at the time Phase VI tests were performed. On one hand, terminating a test series early because of slight rim-to-pavement contact could be construed as “over-reacting” or “not that dangerous to the driver or test surface.” It is possible that early termination of a test series can suppress the detection of two-wheel lift, as it might be produced with higher maneuver entrance speeds. If a test is terminated early, how should the dynamic rollover resistance of the vehicle be reported? Having a vehicle achieve a high rollover resistance rating (no two-wheel lift) by virtue of not being able to perform rollover resistance tests at high speed (due to tire debeading) is obviously undesirable. However, not terminating a test series after rim-to-pavement contact occurs introduces other problems. The behavior of a vehicle during a test that ultimately produces tire debeading is usually violent (e.g., very high lateral accelerations and roll oscillations of increasing magnitude occur). The severity of these tests not only raises test driver safety concerns, but may also increase the wear and tear of the test vehicle substantially. Harming the driver or damaging a vehicle to the point that considerable repair is required can have considerable repercussions.

The occurrence of rim-to-pavement contact and tire debeading confounded the way some Phase VI tests were performed. This section describes how the occurrence of rim-to-pavement contact and tire debeading effected the way NHTSA experimenters were able to execute the Phase VI test matrix on a vehicle-by-vehicle basis. The number presented with each vehicle is the test sequence number; i.e., “Vehicle #9” was the ninth of the twenty-six vehicles evaluated in Phase VI. The question of how to treat rim-to-pavement contact and/or tire debeading was addressed during Phase VII testing, and these results are presented in Chapter 9.

1994 Dodge Caravan (Vehicle #9). Prior to Phase VI, the authors did not believe J-Turns were capable of producing debeading of properly inflated tires[9]. Tests performed with the Dodge Caravan in the Maximum Occupancy configuration proved otherwise. The left front debead occurred during a Maximum Occupancy J-Turn performed with an entrance speed of 59.7 mph. This was the final test of the series, therefore early termination of the series was not necessary. However, the fact that a J-Turn was able to produce a debead resulted in a requirement that inner tubes be installed in each tire for all J-Turns performed after this test.

[9] No J-Turn induced tire debeads were observed during any Phase I-A, I-B, II, III-A, III-B, IV, or V J-Turn test, regardless of vehicle, load configuration, or test speed.

Left front rim-to-pavement contact was observed during a left-right Maximum Occupancy Road Edge Recovery test performed at 45.6 mph. Right-left steering performed in this test series resulted in two instances of right front rim-to-pavement contact. These events occurred during tests performed with 44.9 and 49.6 mph maneuver entrance speeds. None of these tests produced tire debeading. At the time the Caravan was evaluated, rim-to-pavement contact had not yet been established as a series termination criterion. For this reason, combined with the fact no two-wheel lift had been observed, the series was run until the maximum maneuver entrance speeds had been reached for each steering combination.

1997 Ford Ranger 4x4 (Vehicle #11). Left front rim contact occurred during a Maximum Occupancy J-Turn test performed with an entrance speed of 60.9 mph, necessitating the early termination of the series. Although two-wheel lift was produced during this test, the downward iteration of maneuver entrance speed was not performed. For this reason, isolation of the minimum maneuver entrance speed capable of producing two-wheel lift with this steering combination was not possible.

A right front debead occurred during a right-left Road Edge Recovery test performed with an entrance speed of 51.4 mph in the Nominal Load condition. This necessitated the early termination of the series. Since no downward iteration occurred, isolation of the minimum maneuver entrance speed capable of producing two-wheel lift was not possible. The occurrence of the right front debead had no effect on the two-wheel lifts resulting from the input of left-right steering. As with all Road Edge Recovery tests, right-left tests were performed after those using left-right handwheel inputs.

1995 Chevrolet Astro (Vehicle #13). Driver safety considerations required the right steer Maximum Occupancy J-Turn test series be terminated prior to isolation of the minimum two-wheel lift maneuver entrance speed. One of the field experimenters observed that the tread was beginning to separate from the right front tire.

Right *rear* rim contact occurred during a Maximum Occupancy Road Edge Recovery test performed with an entrance speed of 36.8 mph. However, this was the final test of the series, therefore early termination of the series was not necessary.

1998 Honda CR-V (Vehicle #22). Right front rim-to-pavement contact occurred during a left-steer, Maximum Occupancy J-Turn test performed with an entrance speed of 55.2 mph, necessitating the early termination of the series. Two-wheel lift was produced during this test, but since no downward iteration of entrance speed was used, isolation of the minimum maneuver entrance speed capable of producing two-wheel lift with this steering combination was not possible.

Left front rim contact occurred during a left-right, Nominal Load Road Edge Recovery test performed with an entrance speed of 45.9 mph. Two-wheel lift was also produced during this test. Since the occurrence of two-wheel lift necessitated the downward iteration of maneuver entrance speed, and the experimenters did not expect maneuver severity to worsen with diminished entrance speeds, the left-right test series continued until two-wheel lift was no longer observed (five iterations later). These tests did not result in additional rim-to-pavement contact.

A right front rim debead occurred during a right-left, Nominal Load Road Edge Recovery test performed with an entrance speed of 45.4 mph, necessitating the early termination of the series. No two-wheel lift was produced during this test or the two other right-left tests prior to it. Since the final upward entrance speed iteration was not performed, and no downward iteration occurred, isolation of the minimum maneuver entrance speed capable of producing two-wheel lift with this steering combination was not possible.

A left front rim debead occurred during a left-right, Maximum Occupancy Road Edge Recovery test performed with an entrance speed of 43.7 mph, necessitating the early termination of the series. Although two-wheel lift was produced during this test, the downward iteration of entrance speed was not performed. For this reason, isolation of the minimum maneuver entrance speed capable of producing two-wheel lift with this steering combination was not possible.

7.1.4 Why Some Test Series Were Not Performed

A number of cells in Tables 7.1 – 7.3 indicate test series were terminated early or not performed. This section explains of why this was necessary on a vehicle-by-vehicle basis.

1997 Ford Ranger 4x4. Two-wheel lift was produced during left-right and right-left Nominal Load Road Edge Recovery tests performed with the Ford Ranger 4x4. The SSFs of this vehicle in the Nominal Load and Maximum Occupancy conditions were 1.090 and 1.052, respectively. Since the authors do not believe it is possible for increased rollover resistance to coincide with a decrease in SSF for the same vehicle, Maximum Occupancy Road Edge Recovery tests were deemed unnecessary.

1995 Chevrolet K1500, 1997 Ford Ranger 4x2, and 1992 Ford F150. No two-wheel lift was produced during any Maximum Occupancy J-Turn or Road Edge Recovery test performed with the Chevrolet K1500, Ford Ranger 4x2, or Ford F150 (1992). The SSFs of the K1500 in the Nominal Load and Maximum Occupancy conditions were 1.168 and 1.108, respectively. Similarly, the SSFs of the Ranger 4x2 were 1.159 and 1.124, respectively, and the SSFs of the F150 were 1.224 and 1.219, respectively. As previously mentioned, the authors do not believe it is possible for increased rollover resistance to coincide with a decrease in SSF for the same vehicle. Tests performed in the Maximum Occupancy load configuration were thus considered to be "worst case" tests. Since no two-wheel lift occurred with the "worst case" load configurations, Nominal Load testing was deemed unnecessary.

1998 Honda CR-V. Right steer Maximum Occupancy J-Turn tests were performed, however they were terminated after a test begun at 55.6 mph, before the final upward iteration of maneuver entrance speed was complete. Although no rim-contact was made during this final test, the experimenters noted tire wear had reached a critical level (the outer tread blocks were beginning to separate from the tire) and, given the behavior of the vehicle at similar speed in the opposite direction, decided to conclude the test series. It is unknown whether two-wheel lift would have been produced had the series not been terminated after the 55.6 mph test.

A left front debead occurred during a left-right, Maximum Occupancy Road Edge Recovery test performed with an entrance speed of 43.7 mph. The remaining left-right tests, as well as all of those to be performed with right-left steering, were not performed as the series was terminated. Had the debead not occurred, it is unknown whether two-wheel lift would have been produced.

2002 Chevrolet Corvette. Due to its lack of designated rear seating positions and its hatchback configuration, it was not possible to evaluate the Chevrolet Corvette in the Maximum Occupancy load configuration.

7.2 Phase VII Test Results

This section presents a summary of the handwheel angles, two-wheel lifts, instances of rim-to-pavement contact, and tire debeading observed during Phase VII testing. The section has been broken down into two parts: 1) Discussion of results pertaining to J-Turn and Road Edge Recovery tests performed in the Multi-Passenger Configuration, and 2) Discussion of results pertaining to J-Turn and Road Edge Recovery tests performed with various steering scalars. In both parts, two-wheel lift was defined as the occurrence of at least two inches of simultaneous lift of the inside wheels from the test surface. Two-wheel lift less than two inches was not reported. Furthermore, two-wheel lift great enough to require outriggers to suppress roll motion is reported simply as "two-wheel lift" (as long as at least two inches of simultaneous two-wheel lift occurred before outrigger contact with the ground was made).

7.2.1 Multi-Passenger Configuration Test Results

7.2.1.1 Chevrolet Astro

The Chevrolet Astro was the only Phase VI vehicle that only produced two-wheel lift during both Maximum Occupancy test series (i.e., during J-Turn and Road Edge Recover maneuvers). No two-wheel lift was observed during tests performed in the Nominal Load configuration. A possible explanation for this phenomenon was that the number of water dummies used in Phase VI (six) had a much greater impact on rollover propensity than the five water dummies used for each of the other minivans. The Phase VI Maximum Occupancy configuration reduced the SSF of the Astro from 1.126 in the Baseline configuration (no instrumentation or outriggers) to 1.070. This 5.0 percent reduction was greater than that seen for any of the other minivans; the SSFs of the four other minivans were reduced by 0.8 to 4.2 percent[10].

When evaluated in the Multi-Passenger configuration, J-Turn tests performed with the Astro were unable to produce two-wheel lift.

Left-right Road Edge Recovery tests produced two-wheel lift when performed with a maneuver entrance speed of 47.1 mph (12.6 mph greater than that required by the Phase VI Maximum Occupancy configuration). Although right-left tests were able to induce two-wheel lift during

[10] Note that the effect of the Phase VI Maximum Occupancy configuration on the Astro's mass moments of inertia did not follow the same trend. This configuration increased the roll moment of inertia of the Astro by 23.5 percent, within the range of the increase observed by all five Phase VI minivans (21.3 to 32.0 percent). Also, the Maximum Occupancy configuration increased the pitch and yaw inertia of the Astro by the smallest amount (27.4 and 27.2 percent, respectively). These values were up to 10.9 and 10.2 percentage points lower than those observed for the pitch and yaw increases of the other vehicles.

Maximum Occupancy tests performed with entrance speeds as low as 36.2 mph, similar steering was unable to produce tip-up during Multi-Passenger Configuration testing, even with entrance speeds up to 49.6 mph.

Note that the handwheel angles used in the Phase VI Maximum Occupancy configuration were 27.6 percent greater than those used in the Phase VII Multi-Passenger configuration. For reasons discussed in Section 7.2.3, the use of large handwheel inputs does not necessarily impose maximum maneuver severity. As such, it is unlikely the larger Maximum Occupancy handwheel inputs are responsible for the lower measured rollover resistance. Furthermore, the handwheel inputs used for the Nominal Load and Maximum Occupancy configurations were essentially the same, but two very different test outcomes were observed (no two-wheel lift versus two wheel lift at the lowest maneuver entrance speed).

7.2.1.2 Ford Aerostar

Like the Chevrolet Astro, the Ford Aerostar produced two-wheel lift during J-Turn tests performed in the Phase VI Maximum Occupancy configuration. However, unlike the Astro, the Aerostar also produced two-wheel lift in the Multi-Passenger configuration. The handwheel angles used during Multi-Passenger configuration testing were greater than those used during Maximum Occupancy tests.

Despite a reduction of two water dummies, Multi-Passenger Road Edge Recovery tests produced two-wheel lift with a lower entrance speed than that required by the Maximum Occupancy configuration. Note that right-left Road Edge Recovery tests were not performed in the Multi-Passenger configuration. This was because the left-right test performed at 39.7 mph resulted in left front tire debead (loss of all inner tube inflation pressure), and the test series was terminated.

7.2.1.3 Concluding Remarks

Multi-Passenger configuration tests were performed to examine how the use of a standard number of simulated occupants affected the performance of two minivans with known rollover resistance (i.e., measured in Phase VI). In the case of the Ford Aerostar or Chevrolet Astro, the number of water dummies used in the Multi-Passenger configuration was two or three less, respectively, than used during Maximum Occupancy testing.

The placement of the water dummies in the Multi-Passenger configuration differed for each of the two minivans. In the case of the Aerostar, two water dummies were positioned in the second seating row, and one was secured in the center of the third row. Since three second-row seating positions were available in the Astro, all three water dummies were placed in the second row.

Tables 7.4 and 7.5 summarize J-Turn and Road Edge Recovery tests performed with the different water dummy configurations used in Phases VI and VII. When compared to the results obtained during Maximum Occupancy tests, the data indicate use of only three water dummies improved the rollover resistance of the Astro during J-Turn and Road Edge Recovery testing. Conversely, the Multi-Passenger configuration slightly degraded the rollover resistance of the Aerostar from that observed during Maximum Occupancy tests. The disparity of the input conditions (placement of the water dummies) and test outcome (improved or degraded rollover resistance when compared to the Maximum Occupancy results), indicate the Multi-Passenger configuration affects vehicles differently, even if they are members of the same classification category (i.e., minivan).

The Multi-Passenger configuration does offer two desirable attributes, however. First, the Multi-Passenger rollover resistances of the Astro and Aerostar were both degraded from those observed in the respective Nominal Load configurations. Therefore, use of both configurations will allow NHTSA to effectively evaluate the rollover resistance of vehicles at two severity levels. Second, the face validity of the Multi-Passenger loading surpasses that of the Maximum Occupancy configuration. Most passenger vehicles are not typically loaded to the limit of their seating capacity [3]. While not necessarily “worst-case,” Multi-Passenger loading far more likely to be realized during actual driving on public roadways.

Table 7.4. Summary of J-Turn Tests Performed With Different Water Dummy Configurations.

Vehicle	Handwheel Angle (degrees)			Minimum Speed Capable of Producing Two-Wheel Lift (mph)					
	Nominal Load	Maximum Occupancy (Phase VI)	Multi-Passenger Configuration (Phase VII)	Nominal Load		Maximum Occupancy (Phase VI)		Multi-Passenger Configuration (Phase VII)	
				Left	Right	Left	Right	Left	Right
1995 Chevrolet Astro	390	388	304	--	--	--	57.9	--	--
1993 Ford Aerostar	452	451	482	--	--	52.1	--	54.6	--

Note: All tests performed with "standard" J-Turn handwheel angle scalars (8.0).

Table 7.5. Summary of Road Edge Recovery Tests Performed With Different Water Dummy Configurations.

Vehicle	Handwheel Angle (degrees)			Minimum Speed Capable of Producing Two-Wheel Lift (mph)					
	Nominal Load	Maximum Occupancy (Phase VI)	Multi-Passenger Configuration (Phase VII)	Nominal Load		Maximum Occupancy (Phase VI)		Multi-Passenger Configuration (Phase VII)	
				Left-Right	Right-Left	Left-Right	Right-Left	Left-Right	Right-Left
1995 Chevrolet Astro	317	315	247	--	--	34.5	36.2	47.1	--
1993 Ford Aerostar	367	366	392	43.3	46.5	46.5	40.8	39.7	Tests Not Performed

Note: All tests performed with "standard" Road Edge Recovery handwheel angle scalars (6.5).

7.2.2 Reduced Handwheel Scalar Test Results

For some vehicles, the Phase VI test procedures output very large Rollover Resistance Maneuver handwheel angles. Due to the magnitude of these angles, it is possible the vehicle's tires reached saturation before completion of the step steer (J-Turn) or initial steer (Road Edge Recovery). This introduced two problems. First, if the vehicle stopped responding to the initial steer of a Road Edge Recovery input (e.g., maximum roll angle was achieved prior to completion of the steering input), it was not possible for the roll rate feedback-based steering reversals to behave correctly. Second, if a vehicle no longer responds to the commanded steering input, regardless of whether the maneuver is a J-Turn or Road Edge Recovery, the kinetic energy of the vehicle is wasted on excessive tire wear (i.e., due to the large slip angles of the front wheels).

To examine how reductions in the handwheel angles used for J-Turn and Road Edge Recovery maneuvers can affect test outcome, four vehicles were used. Each vehicle was previously evaluated in Phase VI. The handwheel angles were systematically lowered by reducing the magnitudes of the steering scalars used in the methods previously established for Phase VI. Each vehicle was evaluated with handwheel inputs calculated from up to four different steering scalars.

7.2.2.1 J-Turn

The Ford Ranger 4x4 used in Phase VI had been previously evaluated in 1998 during Phase II of NHTSA's Rollover Research Program. In Phase II, the Ranger 4x4 produced "major" two-wheel lift during a right-steer J-Turn performed with a maneuver entrance speed of 52.1 mph. Recall that in Phase II the J-Turn maneuver was comprised of a steering angle of 330 degrees, input at 1000 degrees per second, regardless of vehicle. Also, all Phase II J-Turns were performed in a load configuration nearly equivalent to the Nominal Load configuration used in Phase VI.

In Phase VI, the Ranger 4x4 required a handwheel steering angle of 443 degrees for the J-Turn tests performed in the Nominal Load configuration (also input at 1000 degrees per second). Using these inputs, no two-wheel lift was observed, regardless of steering direction, for speeds up to the 60 mph maximum maneuver entrance speed (the actual maneuver entrance speed was 61.6 mph using right steer).

Recalling that the same vehicle produced "major" two-wheel lift during J-Turns Phase II, NHTSA researchers decided to reduce the handwheel inputs used in Phase VI to those previously used in Phase II after all valid tests had been performed[11]. Using an entrance speed of 61.6 mph, and Phase II steering, the Ranger 4x4 produced substantial two-wheel lift. Given the fact that only two tests separated the 60 mph tests performed with 443 and 330 degree steering inputs, it is

[11] NHTSA researches wanted to insure the comparison between tests performed with different steering angles was as direct as possible. After the termination speed of 60 mph had been achieved using both directions of steer, the Phase VI J-Turn test series was complete. At this point, the decision to perform additional, exploratory tests was made. The tires were inspected, and found to be in acceptable condition. So as to facilitate the most direct comparison of vehicle responses to Phase II and VI and II steering inputs, no tire change was performed. In no way did the inclusion of these extra tests confound the actual ("valid") Phase VI test outcome.

unlikely tire wear was predominately responsible for the extreme differences in test outcome. However, to be sure, the experimenters increased the steering input magnitude back to 443 degrees and performed another test at 60 mph. Using a maneuver entrance speed of 61.4 mph, and 443 degrees of steer, the Ranger 4x4 no longer produced two-wheel lift.

Figure 7.1 compares the two tests performed with 443 degrees of steer to that performed with 330 degrees. These data appear to support the hypothesis that excessive steering actually degrades maneuver severity. This is especially apparent in the yaw rate data traces, where excessive front wheel slide slip significantly reduced the yaw rate achieved during tests performed with 443 degree steering inputs (Tests 0171 and 0176), as compared to that performed with the lesser 330 degree input (Test 0174).

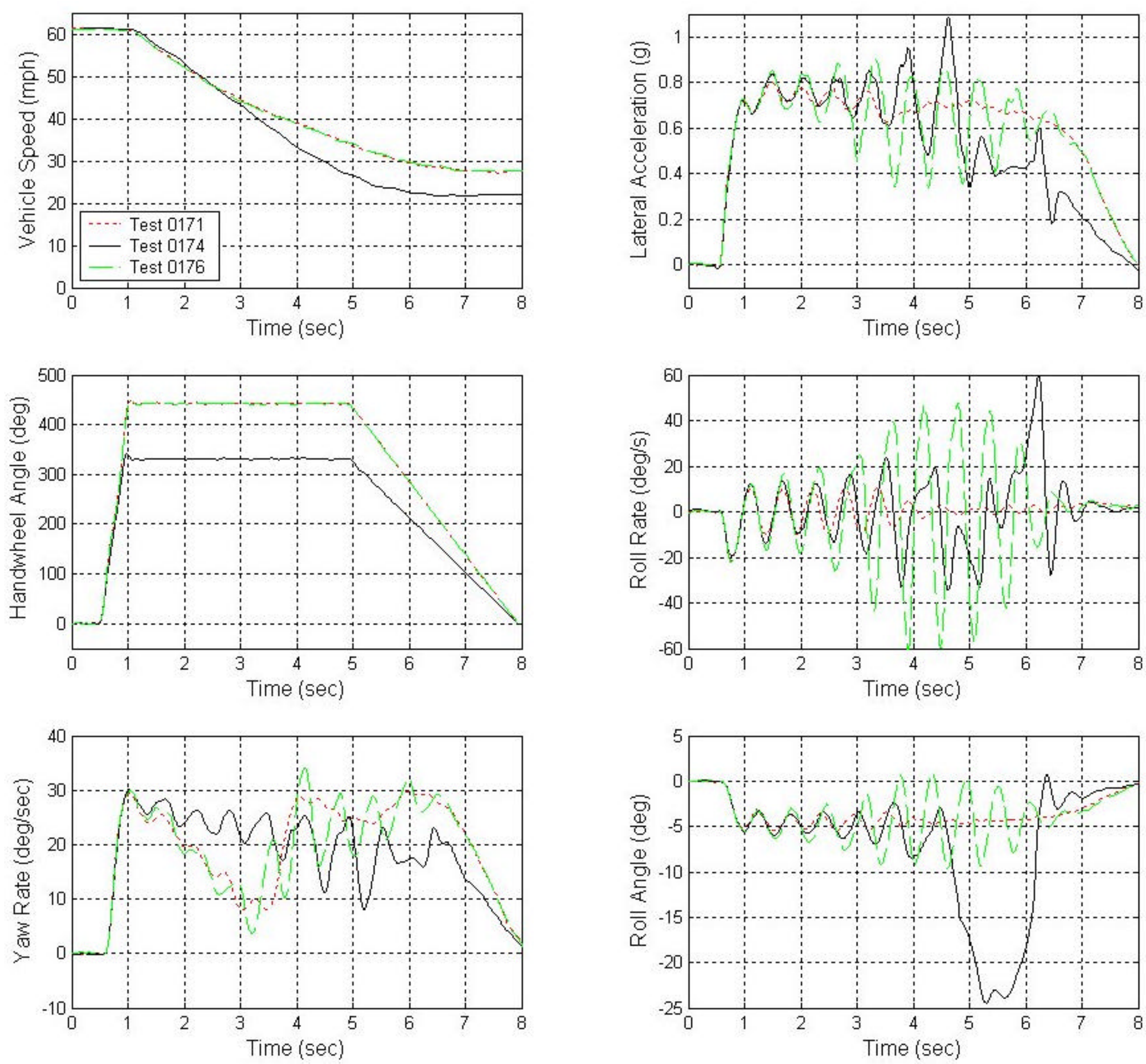


Figure 7.1. Comparison of three J-Turns performed with the 1997 Ford Ranger 4x4.

To address the problems associated with excessive Rollover Resistance Maneuver steering inputs, the authors proposed a reduction in handwheel angle could be easily and consistently achieved by reducing the scalars of each maneuver by 1.0. Phase VII testing explored this proposal.

The default J-Turn steering scalar used in Phase VI was 8.0. As such, the vehicles' responses to the Phase VI J-Turn provide good baseline data against which the Phase VII results may be compared. The only exception is for the Ford Ranger 4x2, where no Nominal Load J-Turns were performed in Phase VI[12]. In the case of the Chevrolet Astro, Ford Aerostar, and Ford Ranger 4x2, Phase VII testing included J-Turns performed with steering scalars of 7.0, 6.0, and 5.0. The Ford Ranger 4x4 used steering scalars of 7.0 and 6.0. Use of a steering scalar equal to 5.0 was not possible with this vehicle. Rim-to-pavement contact was observed when the steering scalar was equal to 6.0, and additional tests were not performed.

For each vehicle, all J-Turns performed with scalars not equal to 8.0 used a common tire set. Depending on the vehicle, eight to thirteen tests were performed for each direction of steer.

Table 7.6 (presented at the end of this section) provides a summary of the J-Turn tests performed with reduced steering scalars. Handwheel angle and two-wheel lift data are given. Each vehicle that produced two-wheel lift during Phase VII J-Turn testing did so when a scalar of 6.0 was used (Aerostar and Ranger 4x4). In the case of the Ranger 4x4, two-wheel lift was also produced during a test performed with steering inputs based on a scalar of 7.0. None of the four vehicles produced two-wheel lift during J-Turns performed with steering inputs based on scalars of 5.0 or 8.0.

Appendix Figures A.1 through A.8 provide traces of representative data for each vehicle. The tests presented in these figures, and discussed in this section, were each performed at approximately 60 mph, the maximum maneuver entrance speed used by NHTSA for J-Turn testing.

When considered on a per vehicle basis, the initial peak yaw rates (i.e., those produced immediately after the steering input) were quite similar regardless of which steering scalar was used. Of greater interest is the manner in which the yaw response of the vehicle degraded after the initial peak had occurred, and how quickly it was able to recover. The extent to which steering scalar magnitude was responsible for the magnitude of these "dips" in yaw rate responsiveness was vehicle dependent, and somewhat asymmetric. For example, consider the results obtained from right steer tests performed with the Chevrolet Astro (see Figure A.1). When a steering scalar of 8.0 was used, the Astro's ability to respond to the commanded steering input degraded much sooner than during similar tests based on lesser scalars. This was not the case when steering to the left was used (as shown in Figure A.2).

The lateral acceleration and roll angle responses resulting from the use of the various steering scalars were more disparate (i.e., the various scalars affected the roll motion of the vehicles in

[12] Only Maximum Occupancy J-Turns were performed with the Ford Ranger 4x2 in Phase VI. No two-wheel lift was observed during these tests when a steering scalar of 8.0 was used. Since Maximum Occupancy tests were considered to be "worst-case," Nominal Load testing was deemed unnecessary in the interest of timesavings.

different ways). The vehicle/scalar/direction of steer combinations capable of producing roll oscillations in one vehicle may not have produced the same response in another. For example, use of handwheel angles based on a scalar of 6.0 clearly imposed the greatest maneuver severity during right-steer tests performed with the Ranger 4x4, as shown in Figure A.7. The steering angles associated with this test allowed the vehicle's roll oscillations to build much faster, and ultimately to a much greater level, than those observed during tests performed with scalars of 7.0 and 8.0. Conversely, a steering scalar of 7.0 induced the greatest maneuver severity when right-steer tests were performed with the Ranger 4x2, as shown in Figure A.5.

Table 7.6. Summary of Phase VII J-Turn Tests Performed With Decreased Handwheel Scalars.
(All Tests Performed in the Nominal Load Configuration)

Vehicle	Steering Scalar	Minimum Entrance Speed Capable of Producing Two-Wheel Lift (mph)	
		Left	Right
1995 Chevrolet Astro	8.0	--	--
	7.0	--	--
	6.0	--	--
	5.0	--	--
1993 Ford Aerostar	8.0	--	--
	7.0	--	--
	6.0	57.0	--
	5.0	--	--
1997 Ford Ranger 4x2	8.0	Tests Not Performed	
	7.0	--	--
	6.0	--	--
	5.0	--	--
1997 Ford Ranger 4x4	8.0	--	--
	7.0	--	58.2
	6.0	59.0	59.6
	5.0	Tests Not Performed	

7.2.2.2 Road Edge Recovery

Certain combinations of handwheel steering angle, vehicle speed, and load configuration resulted in some Phase VI test vehicles reaching maximum roll angle *before* completion of the initial Road Edge Recovery steering input. When this phenomenon occurred, it was not possible for the maneuver to be performed as intended (i.e., reversing direction of steer at maximum roll angle).

As programmed for NHTSA Road Edge Recovery testing, the steering machine commands steering reversals when two criteria are satisfied *in sequence*. First, the initial steer must be complete. Second, the vehicle's roll rate must be within the its window comparator (∀1.5 degrees per second). The reversal occurs the instant the second criterion is satisfied[13]. In other words, even though maximum roll angle has been achieved, the reversal cannot occur until completion of the initial steer. This can significantly increase maneuver input repeatability if max roll angle occurs prior to completion of the initial steer, as demonstrated in Figure 7.2.

Figure 7.2 presents four Road Edge Recovery tests performed with the Ranger 4x4 in the Nominal Load configuration. In every test, maximum roll angle is achieved prior to completion of the initial steer. For the tests begun at 36.3 and 41.8 mph (Tests 0178 and 0179, respectively), dwell time was zero; the reversals occurred immediately after the initial steer inputs were complete. This was because the roll rate signal was still within the steering machine's roll rate window comparator at the instant the initial steer inputs were complete, thus satisfying the second reversal criteria.

Now consider the tests begun at 45.9 and 51.2 mph (Tests 0180 and 0181, respectively). Unlike the tests begun at 36.3 and 41.8 mph, the roll rate signal was not within the roll rate window comparator thresholds when the initial steering inputs were complete, therefore the second reversal criteria was not met. For this reason the steering machine waited for the next roll rate zero crossing before initiating the reversal. Unfortunately, the reversal occurred in response to the *second* local roll angle peak, not the first as intended. As a result, the preservation of roll motion was not optimized (although two wheel lift was still produced during the test begun at 51.2 mph). This was addressed in Phase VII.

[13] In its present configuration, the steering machine must execute command code on a line-by-line basis. Since code commanding the initial handwheel ramp occurs before that commanding the reversal, the ramp must be completed before the controller considers the criterion governing the reversal (roll rate . 0).

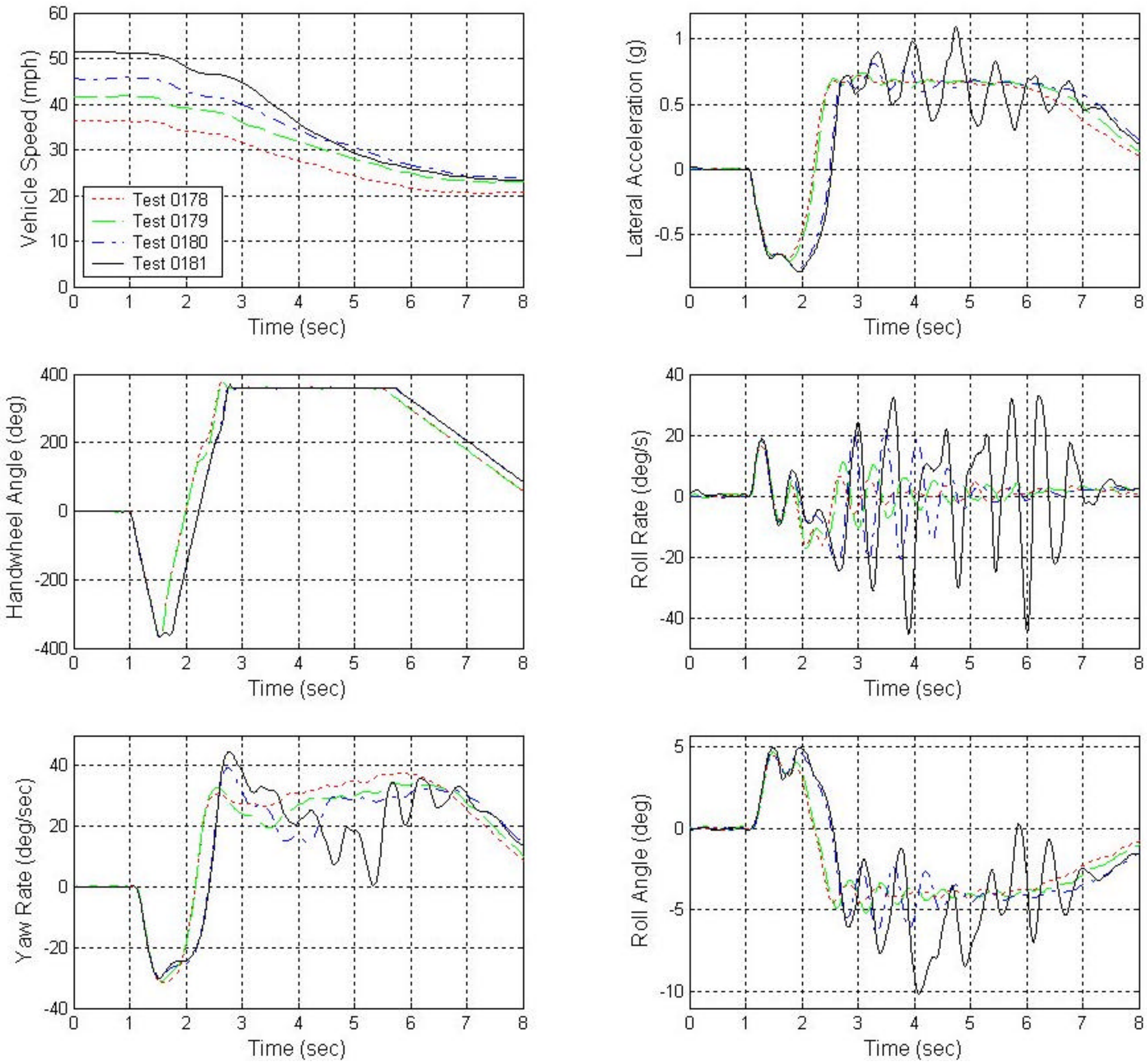


Figure 7.2. Comparison of four Road Edge Recovery tests performed with the 1997 Ford Ranger 4x4.

The default Road Edge Recovery steering scalar for Phase VI was 6.5. As such, the vehicles' responses to the Phase VI Road Edge Recovery tests provide good baseline data for which to compare Phase VII results against. The only exception was for the Ford Ranger 4x2, where no Nominal Load Road Edge Recovery tests were performed in Phase VI[14]. In the case of the Chevrolet Astro and Ford Ranger 4x2, Phase VII testing included Road Edge Recovery maneuvers performed with steering scalars of 5.5, 4.5, and 3.5. The Ford Aerostar and Ford Ranger 4x4 used steering scalars of 5.5 and 4.5. Use of a steering scalar equal to 3.5 was not possible for these vehicles due to excessive tire wear (Aerostar) or early test series termination due to rain (Ranger 4x4).

[14] Only Maximum Occupancy J-Turns were performed with the Ford Ranger 4x2 in Phase VI. No two-wheel lift was observed during these tests. Since Maximum Occupancy tests were considered to be "worst-case," Nominal Load testing was deemed unnecessary in the interest of timesavings.

For each vehicle, all Road Edge Recovery tests performed with scalars not equal to 6.5 used a common tire set. Depending on the vehicle, the six to ten tests were performed with each steering combination (i.e., left-right or right-left inputs).

Table 7.7 provides a summary of the Road Edge Recovery tests performed with decreased steering scalars. Handwheel angle and two-wheel lift data are presented. None of the four vehicles produced two-wheel lift during Road Edge Recovery tests performed with steering inputs based on scalars of 3.5 (Astro and Ranger 4x2) or 4.5. In the case of the Aerostar, steering inputs based on scalars of 5.5 and 6.5 were able to produce two-wheel lift. Only the use of steering inputs based on a scalar of 6.5 was able to produce two-wheel lift with the Ranger 4x4.

For each vehicle, reducing the steering magnitude resulted in an increase in dwell time. For each vehicle, a steering scalar reduction of 1.0 was great enough that there was no overlapping in the ranges of dwell times associated with each scalar, as shown in the third column of Table 7.7. This is important for two reasons:

First, a very short dwell time indicates the vehicle was being operated with steering that was nearly saturating the tires. As previously discussed, instances where the steering inputs include a dwell time of less than 80 ms indicate the respective steering reversals were commanded at nearly the same instant the vehicle had achieved maximum roll angle. This timing implies that if additional steering were to be used, it would be "excessive," i.e., the vehicle would not be able to respond to the entire initial steer input. So in this regard, dwell time duration can be used as an indicator of tire saturation.

Secondly, the lack of any dwell time duration overlap also implies a reduction of 1.0 is great enough to have a significant influence on how the vehicle will respond to the maneuver. If maximum roll angle is produced prior to completion of the initial steer when a steering scalar of 6.5 is used, the data presented in Table 4.4 indicate a scalar reduction of 1.0 is generally enough to ensure the tires are not overly saturated.

As shown in Figures A.9 through A.16, reduction of the handwheel scalars clearly affected the yaw and roll responses of each vehicle. When compared to similar results observed during J-Turn testing, Road Edge Recovery results were more disparate. This was likely due to the fact the Road Edge Recovery tests include two, rather than one, primary steering inputs and that the handwheel steering angles and rates differed from those used in the J-Turn.

The test outputs resulting from the use of different steering scalars often produced similar trends and peak values, however the magnitudes of the scalars capable of producing the most similar responses depended on the vehicle being considered. For example, Figures A.11 and A.12 show the yaw rate responses produced during Aerostar tests performed with steering inputs based on scalars of 5.5 and 6.5 were quite similar. However, perusal through Figures A.13 through A.16 indicate the tests performed with the Ranger 4x2 and Ranger 4x4 were most similar when scalars of 4.5 and 5.5 were used. Of the four vehicles evaluated with the various steering scalars in Phase VII, only tests performed with the Astro produced peak yaw rate responses that increased as a function of scalar magnitude for each of the four scalars used in this study. This effect was most pronounced in response to the yaw produced by the steering reversals. The Astro tests are shown in Figures A.9 and A.10.

As was the case with the J-Turn maneuver, the lateral acceleration and roll angle responses produced with the various Road Edge Recovery steering scalars were more disparate than the yaw responses observed during the same tests. When considered on a per-vehicle basis, the peak lateral accelerations and roll angles resulting from the initial steer were generally very similar, regardless of steering scalar magnitude. Exceptions to this trend include tests performed with the Astro and left-right test performed with the Ranger 4x4. In the case of the Astro, the magnitude of the peak lateral acceleration and roll angle responses to the initial steer increased as a function of steering scalar magnitude (in a manner similar to the way the vehicle responded in yaw). Results observed during tests performed with the Ranger 4x4 are discussed later in this section.

Most of the lateral acceleration and roll angle response disparity appears in the vehicles' post-reversal behavior. Specifically, the vehicle/scalar/steering combinations capable of producing roll oscillations in one vehicle may not have produced the same response in another. Generally speaking, use of handwheel angles based on the largest steering scalars used for a particular vehicle produced the greatest post-reversal responses for that vehicle. The extent to which the peaks produced with the various scalars depended on the vehicle being considered. For example, Figure A.12 shows the Aerostar's peak post-reversal lateral acceleration and roll angles produced with right-left steering inputs based on scalars of 5.5 and 6.5 were nearly identical, and that their magnitudes were much greater than those produced by the same vehicle when steering based on the smallest scalar (4.5) was used. Conversely, the left-right tests performed with the Astro (see Figure A.9) produced the smallest post-reversal lateral acceleration when the steering inputs based on the largest scalar (6.5) were used.

Table 7.7. Summary of Phase VII Road Edge Recovery Tests Performed With Decreased Handwheel Scalars. (All Tests Performed in the Nominal Load Configuration)

Vehicle	Scalar	Dwell Time Range (ms)	Minimum Entrance Speed Capable of Producing Two-Wheel Lift (mph)	
			Left-Right	Right-Left
1995 Chevrolet Astro	6.5	70 - 90	--	--
	5.5	125 - 140	--	--
	4.5	170 - 180	--	--
	3.5	215 - 230	--	--
1993 Ford Aerostar	6.5	n/a* - 35	43.3	46.5
	5.5	95 - 115	49.0	44.2
	4.5	155	--	--
	3.5	Tests Not Performed		
1997 Ford Ranger 4x2	6.5	Tests Not Performed		
	5.5	100 - 125	--	--
	4.5	155 - 175	--	--
	3.5	195 - 205	--	--
1997 Ford Ranger 4x4	6.5	n/a*	48.8	51.4
	5.5	60 - 85	--	--
	4.5	125	--	--
	3.5	Tests Not Performed		

*Maximum roll angle was achieved before completion of the initial steer.

7.2.2.3 Comments on the Occurrence of "Excessive" Steering

The concept of using a roll rate feedback control loop to initiate handwheel reversals represents an attempt by NHTSA to "optimize" the Road Edge Recover maneuver. By commanding steering reversals to occur very near the maximum roll angle produced with the initial steer, the intent is to preserve the roll motion of the vehicle to the greatest extent possible as it transitions from one steering direction to the next. In essence, the roll rate feedback control loop allows the vehicle to seek out its own roll angle natural frequency.

It is for this reason that the Ranger 4x4 produced some of the more interesting results seen in Phase VII. When a steering scalar equal to 6.5 was used in conjunction with maneuver entrance speeds of 45 mph or greater, maximum roll angle was achieved prior to completion of the initial steering input, as mentioned in Table 7.7 and shown in Figure A.15. Despite the roll motion of the vehicle being disturbed, the peak magnitudes of the post-reversal yaw and roll responses were greater than those produced during tests performed without the "erroneous" dwell time, i.e., those performed with scalars equal to 4.5 or 5.5.

When the Ranger 4x4 was evaluated with steering inputs based on a scalar of 6.5, the dwell times produced were longer than those produced with the lesser scalars. This is because when this scalar was used, the steering machine was unable to complete the initial steer before the vehicle achieved maximum roll angle. By the time the initial steer was complete, the vehicle had begun to roll back (the normal load of the inside wheels began increase). The vehicle then began to oscillate in roll, and in doing so reached a second roll angle peak. It was at this instant the steering reversal was actually executed – at the second roll rate zero crossing.

What makes the Ranger 4x4 tests interesting is that even though the roll motion was theoretically impeded due to the unintentional timing of the steering reversal, tests performed with a steering scalar equal to 6.5 produced greater peak roll angles than did the tests performed with lesser scalars. Furthermore, 6.5 was the only steering scalar able to produce two-wheel lift. Tip-ups occurred using both steering combinations with this scalar. The use of lesser steering scalars was unable to produce two-wheel lift.

7.2.2.4 Concluding Remarks

The intent of this section was to demonstrate that the reduction of steering scalars could improve the effectiveness of NHTSA's Rollover Resistance maneuvers. As such, adjustments to the existing test procedures that incorporate the use of reduced steering scalars are recommended. This will help to ensure high maneuver severity even if the Road Edge Recovery test procedure results in the use of excessive steering.

In the case of the J-Turn maneuver, the use of steering scalars less than 6.0 do not appear to be advantageous. For two of the four vehicles evaluated with reduced steering scalars (the Ford Aerostar and Ford Ranger 4x4), scalars of 6.0 and/or 7.0 were able to produce two-wheel lift, while scalars of 5.0 and 8.0 were not. These results are encouraging since changes to the existing J-Turn test procedure can easily incorporate the use of lesser scalars to promote maximum maneuver severity.

In the case of the Road Edge Recovery maneuver, the use of steering scalars less than 5.5 does not appear to be advantageous. Of the four vehicles evaluated, only the Ford Aerostar was able to produce two-wheel lift with a reduced steering scalar. When right-left steering was used in conjunction with a steering scalar of 5.5, the minimum maneuver entrance speed for which two-wheel lift occurred was 2.3 mph less than that required when the default scalar of 6.5 was used.

Like the J-Turn results, these results are encouraging since changes to the existing Road Edge Recovery test procedure can easily incorporate the use of a lesser scalar to promote maximum maneuver severity.

7.2.3 Increased Handwheel Scalar Test Results

For some vehicles, it is possible the Phase VI test procedure may have output handwheel angles small enough that maximum maneuver severity was not achieved. To address this potential shortcoming, the authors proposed an increase in handwheel angle could be easily and consistently achieved by increasing the scalars of each maneuver by 1.0. Rather than multiplying the handwheel angle producing an average lateral acceleration of 0.3 g in the Slowly Increasing Steer Maneuver by a scalar of 6.5 for the NHTSA Road Edge Recovery or by a scalar of 8.0 for the NHTSA J-Turn, the scalars would be 7.5 and 9.0, respectively. For Phase VII, this concept was explored.

No two-wheel lift was observed during any J-Turn or Road Edge Recovery performed with the 2001 Ford Explorer 4x2, regardless of the steering scalar magnitude. The commanded handwheel angles and their respective ranges are shown in Table 7.8. In the case of the of Road Edge Recovery maneuver, the dwell times corresponding to each scalar are also provided. All Explorer 4x2 tests used to evaluate the effects of increasing handwheel scalars were performed in the Nominal Load configuration.

Table 7.8. Summary of 2001 Ford Explorer 4x2 J-Turn Tests Performed With Increased Handwheel Scalars.

Maneuver	Scalar	Dwell Time Range (ms)	Two-Wheel Lift?
J-Turn	8.0	N/A	No
	9.0	N/A	No
	10.0	N/A	No
Road Edge Recovery	6.5	110 - 145	No
	7.5	85 - 120	No
	8.5	40 - 65	No

Table 7.8 shows that increasing the Road Edge Recovery steering scalar from 6.5 to 8.5 resulted in a corresponding decrease in dwell time. These results also indicate the benefits of having an optimized dwell time may not be fully realized when scalars ≥7.5 are used. This is because the steering machine has a small mechanical overshoot after completion of the initial steering ramp. Since the duration of this overshoot typically lasts about 80 ms, tests with dwell times less than about 80 ms may appear no different those with zero dwell times to the vehicle.

Figures 7.3 and 7.4 each compare three Road Edge Recovery tests performed with maneuver entrance speeds of approximately 50 mph. Note that the use of large handwheel angles does not necessarily insure maneuver severity is maximized. For example, comparison of the test outputs presented on Figure 7.4 demonstrates that the use of the smallest handwheel angles produced the greatest yaw rate, lateral acceleration, and roll angle responses to the initial steer and steering reversals.

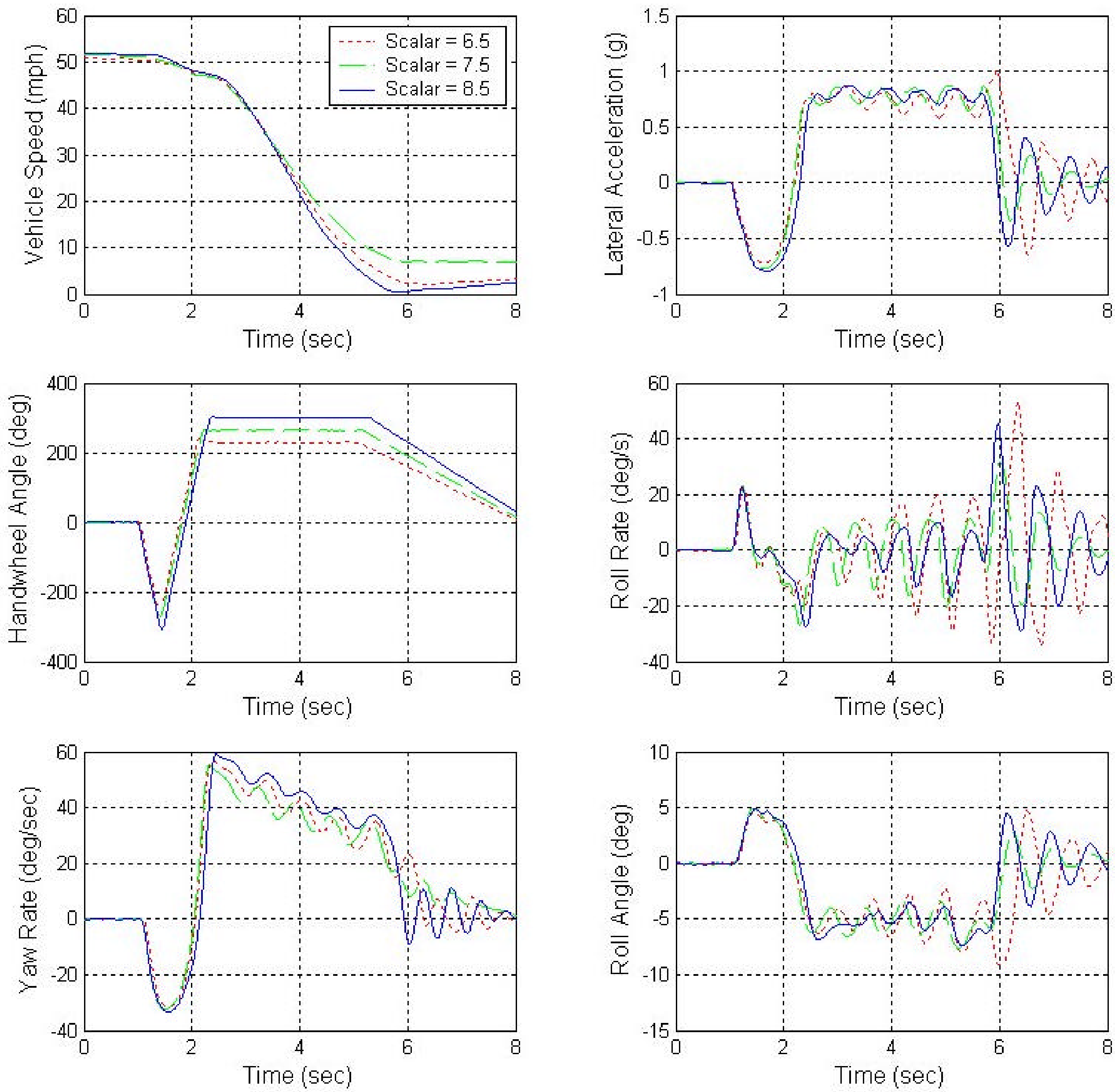


Figure 7.3. Left-right Road Edge Recovery tests performed with a 2001 Ford Explorer 4x2 using three steering scalars.

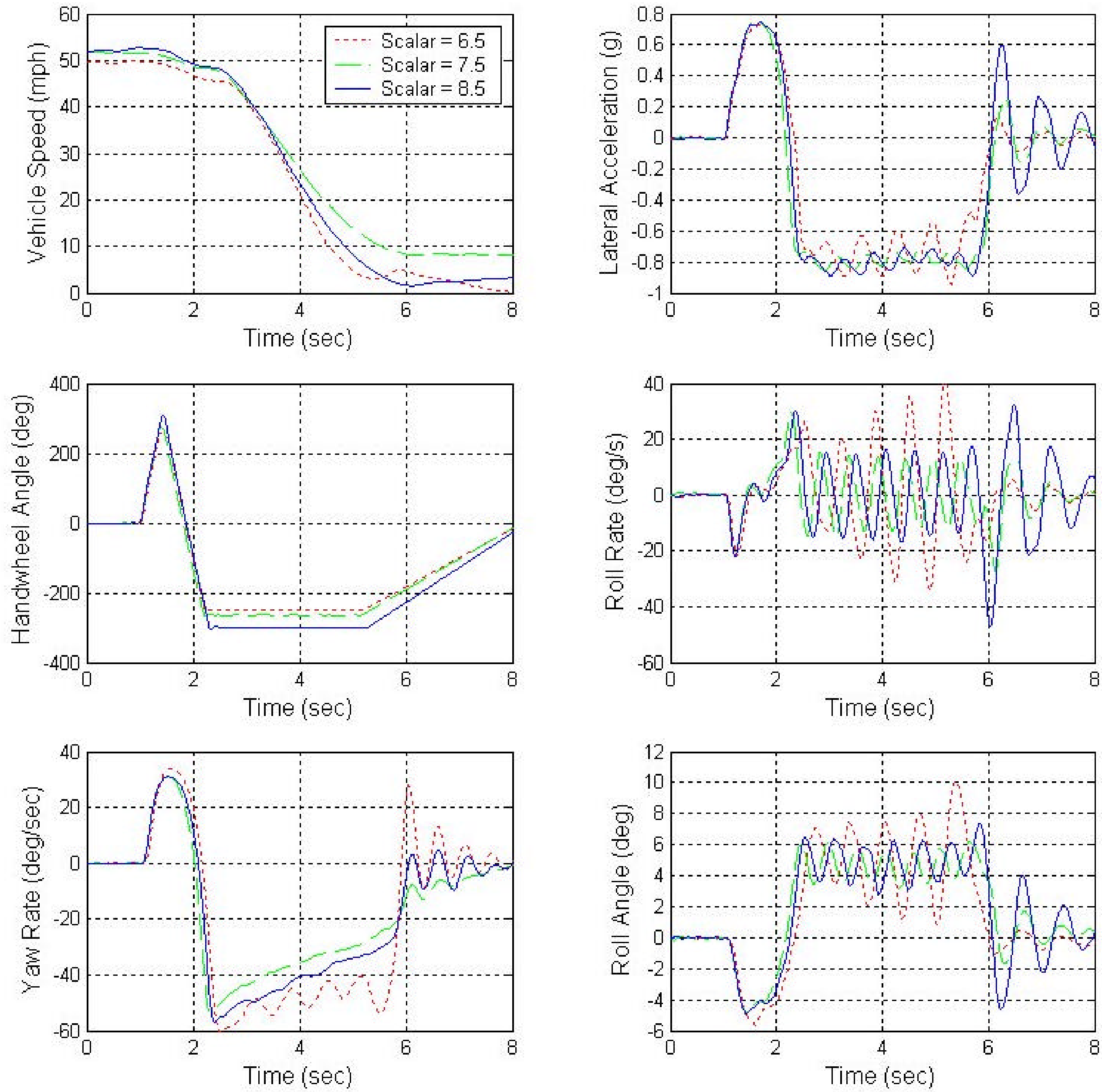


Figure 7.4. Right-left Road Edge Recovery tests performed with a 2001 Ford Explorer 4x2 using three steering scalars.

8.0 TWO-WHEEL LIFT REPEATABILITY

The manner in which most Phase VI Rollover Resistance Maneuvers were executed provided a good way of assessing how repeatable the occurrence of two-wheel lift was for tests performed with nearly identical maneuver entrance speeds. If two wheel lift was produced during a particular test series, the experimenters were generally able to reduce the maneuver entrance speeds in 1 mph increments until two-wheel lift was no longer produced[15]. The experimenter would then increase the maneuver entrance speed back to that which had previously produced two-wheel lift and perform [repeat] two tests.

Chapter 8 describes the test repeatability of the NHTSA J-Turn and NHTSA Road Edge Recovery maneuvers. Since the input repeatability of these maneuvers has been well documented, this chapter focuses on the two-wheel lift repeatability of tests performed with nearly equivalent maneuver entrance speeds.

8.1 NHTSA J-Turn

Table 8.1 presents two-wheel lift data for three test vehicles. Although two-wheel lift was observed during J-Turns performed with six vehicles in Phase VI, tests performed with the Ford Ranger 4x4 and Chevrolet Astro were not conducive to the repeatability assessment made in this chapter due to early termination of the respective test series. Although the lowest maneuver entrance speed capable of producing two-wheel lift was isolated for the Ford Aerostar, the two two-wheel lift repeatability tests were not performed due to experimenter concerns regarding excessive tire shoulder wear.

The data presented in Table 8.1 are sorted first by load configuration, then by direction of steer. For each direction of steer, there are three columns. The first is the lowest entrance speed for which two-wheel lift was produced during the downward iteration of vehicle speed. The second and third columns contain maneuver entrance speeds for the two tests intended to assess two-wheel lift repeatability. Note that "--" indicates no two-wheel lift occurred for a given vehicle/load/steering test condition.

The three right steer Maximum Occupancy J-Turns performed with the Mitsubishi Montero began with maneuver entrance speeds within 0.4 mph of each other. Each test produced two-wheel lift.

In the case of the Acura SLX, the range of maneuver entrance speeds for tests performed within a load/steer condition were within 0.8 mph of each other. With Nominal Load, two-wheel lift was observed during a left steer test performed at 39.9 mph, but not at 39.5 or 39.1 mph. In the Maximum Occupancy configuration, tests begun at 34.8 and 34.6 mph produced two-wheel lift, while the test performed at 34.2 mph did not. Although NHTSA's two-wheel lift criteria was not

[15] Factors such as pavement-to-rim contact, tire debeading, and/or tread separation necessitated early termination of some Rollover Resistance maneuvers. In these cases, isolation of the minimum maneuver entrance speed capable of producing two-wheel lift for certain test conditions was not possible.

fulfilled for some SLX tests (two inches of simultaneous two-wheel lift was not observed), these tests *did* produce some two-wheel lift; it was just less than two inches.

The range of maneuver entrance speeds for Chevrolet Blazer tests performed at Maximum Occupancy were within 1.3 mph of each other for a given a steer condition. With left steering, two-wheel lift was observed during left steer tests performed at 53.7 and 52.4 mph, but not at 52.6 mph. In a manner similar to that previously mentioned for the Acura SLX, the Blazer test performed at 52.6 mph did produce some two-wheel lift, just not enough to meet NHTSA's definition of such lift. When right steering was input, tests begun at 49.0 and 49.5 mph produced two-wheel lift, while the test performed at 49.6 mph did not. The test performed at 49.6 mph did not produce two-wheel lift, however. Only front wheel lift was observed.

8.2 NHTSA Road Edge Recovery

Table 8.2 presents two-wheel lift data for ten test vehicles. The data are sorted first by load configuration, then by steering combination. For each steering combination, there are three columns. The first is the lowest entrance speed for which two-wheel lift was produced during the downward iteration of vehicle speed. The second and third columns contain maneuver entrance speeds for the two tests intended to assess two-wheel lift repeatability. Note "-" indicates that either no two-wheel lift occurred for a given vehicle/load/steering test condition or that even though two-wheel lift did occur, the particular set of test conditions were not conducive to the repeatability assessment made in this chapter.

For each vehicle/load/steering conditions presented in Table 8.2, the Toyota 4Runner, Acura SLX, Ford Explorer 4x4, Ford Ranger 4x4, and Chevrolet Astro produced two-wheel lift during each of the three tests. This was also true for three of the four vehicle/load/steering conditions presented in Table 8.2 for the Chevrolet Blazer, and two of the four vehicle/load/steering conditions for the Mitsubishi Montero and Ford Aerostar. For these vehicles, in the conditions mentioned, the overall speeds differed by up to 1.7 mph per vehicle. The average difference was 0.6 mph.

For certain vehicle/load/steering conditions presented in Table 8.2, the Honda CR-V, Chevrolet Tracker, and Chevrolet Blazer produced less than two inches of two-wheel lift for some tests, while others resulted in lift greater than or equal to two-inches. With left-right steering in the Nominal Load configuration, CR-V tests performed at 42.4 and 42.5 mph satisfied NHTSA's definition of two-wheel lift, while a test performed at 42.1 mph did not. When right-left steering was used during Maximum Occupancy tests performed with the Tracker, a 45.8 mph test satisfied NHTSA's definition of two-wheel lift, while tests performed at 45.9 and 45.8 mph did not. In the case of the Blazer, left-right steering used in the Maximum Occupancy configuration produced two-wheel lift greater than or equal to two-inches when maneuver entrance speeds of 34.9 and 35.7 were used, but not when 36.8 mph was used. For these vehicles, in the conditions mentioned, the overall speeds differed by up to 1.9 mph per vehicle. The average difference was 0.9 mph.

Table 8.2 shows that when the Chevrolet Tracker and Ford Aerostar were evaluated with certain combinations of loading and steering, two-wheel lift greater than or equal to two-inches was observed during some tests, but only front wheel lift was produced during others. When left-right steering was used in the Maximum Occupancy configuration with the Tracker, a test begun at 43.5 mph produced two-wheel lift, while tests performed at 43.4 and 43.2 mph only produced lift of the inside front tire. In the case of the Aerostar, left-right steering input in the Nominal Load configuration resulted in two-wheel lift when maneuver entrance speeds of 44.0 and 43.3 mph were used. Use of a 43.0 mph entrance speed in this test condition only produced front wheel lift. Similar results for the Aerostar were also observed when right-left steering was used in conjunction with the Maximum Occupancy load configuration. Tests performed at 40.8 and 41.1 mph produced two-wheel lift, while a test begun at 40.8 mph only resulted in front-wheel lift. For these vehicles, in the conditions mentioned, the overall speeds differed by up to 1.0 mph per vehicle. The average difference was 0.5 mph.

In the case of the Mitsubishi Montero, two of the four vehicle/load/steering conditions presented in Table 8.2 produced two-wheel lift for some tests but not for others. When left-right steering was used in the Nominal Load configuration, two tests begun at 32.7 mph resulted in two-wheel lift, while a 32.9 mph test resulted in no two-wheel lift of any magnitude. Similar results were observed during right-left tests performed in the Maximum Occupancy configuration with this vehicle. Tests begun at 29.7 and 30.1 mph resulted in two-wheel lift, while another 30.1 mph test resulted in no two-wheel lift of any magnitude. In the conditions mentioned, the overall speeds differed by up to 0.4 mph per vehicle. The average difference was 0.3 mph.

8.3 Two-Wheel Lift Repeatability Summary

At first glance, the data presented in Tables 8.1 and 8.2 may appear to indicate two-wheel lift is not a very repeatable phenomenon. The authors do not believe this is necessarily the case. While any test variability is undesirable, it is important to acknowledge the vehicles mentioned in Table 8.1 were being evaluated at their two-wheel lift threshold speeds (the maneuver entrance speed for which two-wheel lift may or may not occur). When operating at these thresholds, the propensity for two-wheel lift is very high, but not absolutely assured.

The influence of two-wheel lift repeatability on the consumer information program required by the TREAD Act depends to some extent on how the Rollover Resistance Maneuver test results are used. If this program treats two-wheel lift as a binary result (i.e., it either does or does not occur), two-wheel lift variability would only affect vehicles whose two-wheel lift thresholds are at the maximum maneuver entrance speed associated with each maneuver. If the minimum maneuver entrance speed capable of producing two-wheel lift is considered, differences between good and poor rollover resistance may be more specific, however as the number of criteria necessary to achieve a particular rating will increase, the likelihood of threshold variability affecting the final outcome becomes greater (e.g., how the minimum maneuver entrance speed capable of producing two-wheel lift for each maneuver/load combination of a 3-star rating differs from that of a 2-star rating).

Thresholds must exist for every rating system, not just those based on dynamic test results. Even the current SSF-based rollover resistance metric faces this dilemma. For example, it is possible popular options such as glass sunroofs can reduce the SSFs of the respective vehicles just enough for their [static] Rollover Resistance rating to be one-star lower than otherwise equivalent models.

Table 8.1. J-Turn Maneuver Entrance Speed Versus Two-Wheel Lift Repeatability Check.

Vehicle	Nominal Load						Maximum Occupancy					
	Left Steer			Right Steer			Left Steer			Right Steer		
	Initial	1st Repeat	2nd Repeat	Initial	1st Repeat	2nd Repeat	Initial	1st Repeat	2nd Repeat	Initial	1st Repeat	2nd Repeat
1996 Acura SLX	39.9	39.5 (No TWL)[1]	39.1 (No TWL)[1]	--	--	--	34.8	34.2 (No TWL)[1]	34.6	--	--	--
2001 Chevrolet Blazer				--	--	--	53.7	52.6 (No TWL)[1]	52.4	49.0	49.5	49.6 (No TWL)[2]
1995 Mitsubishi Montero				--	--	--				30.6	31.0	31.0
1993 Ford Aerostar				--	--	--				--	--	--

(No TWL)[1] = less than two inches of simultaneous two wheel lift was observed
(No TWL)[2] = front wheel lift only, no rear wheel lift
(No TWL)[3] = no front or rear wheel lift

Table 8.2. Road Edge Recovery Maneuver Entrance Speed Versus Two-Wheel Lift Repeatability Check.

Vehicle	Nominal Load						Maximum Occupancy					
	Left-Right Steering			Right-Left Steering			Left-Right Steering			Right-Left Steering		
	Initial	1st Repeat	2nd Repeat	Initial	1st Repeat	2nd Repeat	Initial	1st Repeat	2nd Repeat	Initial	1st Repeat	2nd Repeat
1998 Honda CR-V	42.4	42.5	42.1 (No TWL)[1]	--	--	--				--	--	--
1998 Chevrolet Tracker				--	--	--	43.5	43.4 (No TWL)[2]	43.2 (No TWL)[2]	45.4	45.9 (No TWL)[1]	45.8 (No TWL)[1]
2001 Toyota 4Runner*				--	--	--	37.2	37.6	37.7	45.8	45.8	45.7
1996 Acura SLX	39.5	39.9	39.5	--	--	--	36.0	35.3	35.7	35.9	36.5	36.5
2001 Ford Explorer XLS				--	--	--	38.6	37.5	39.2	--	--	--
2001 Chevrolet Blazer	40.4	40.6	40.7	39.8	40.4	39.6	34.9	35.7	36.8 (No TWL)[1]	35.2	34.3	34.3
1995 Mitsubishi Montero	32.7	32.7	32.9 (No TWL)[3]	40.6	40.7	41.0	34.6	34.6	34.0	29.7	30.1	30.1 (No TWL)[3]
1997 Ford Ranger 4x4	49.3	49.8	48.8	--	--	--				--	--	--
1995 Chevrolet Astro				--	--	--	34.9	34.6	34.5	36.2	36.8	36.8
1993 Ford Aerostar	44.0	43.3	43.0 (No TWL)[2]	46.5	47.0	46.7	47.2	46.6	46.5	40.8	41.1	40.8 (No TWL)[2]

*The electronic stability control (VSC) installed on the model year 2001 4Runner was disabled during all tests performed in Phase VI. Since the only significant difference between model year 2000 and 2001 4Runners is the presence of stability control (not available in 2000, standard equipment in 2001), the performance of the 2001 model with disabled stability control is representative of an otherwise equivalent 2000 model.

(No TWL)[1] = less than two inches of simultaneous two wheel lift was observed
(No TWL)[2] = front wheel lift only, no rear wheel lift
(No TWL)[3] = no front or rear wheel lift

9.0 RESOLUTION OF CONCERNS IDENTIFIED IN PHASE VI

As stated earlier in this report, the "substantial number of diverse test vehicles used in Phase VI allowed NHTSA to realize maneuver severity may be better optimized if some minor adjustments to the test procedure were implemented." The authors also acknowledged that the Maximum Occupancy configuration was in need of further refinement and a means of reporting tire debeading and rim-to-pavement contact should be developed.

Section 7.2 of this report explained how use of a standardized water dummy configuration, i.e., the "Multi-Passenger" loading, can improve the consistency of which the dummies are used while preserving NHTSA's ability to evaluate vehicles at two severity levels. Also discussed was how adjustments to the J-Turn and Road Edge Recovery test procedures can be used to improve these maneuvers via manipulation of steering scalar magnitude.

This chapter addresses issues pertaining to the reporting of tire debeading and rim contact, and provides a formal definition of the Multi-Passenger configuration.

9.1 Should a test series be terminated if rim-to-pavement contact occurs?

NHTSA performs all rollover resistance maneuvers with inner tubes installed in each tire. This is because Phase IV testing demonstrated the use of inner tubes can reduce damage to the test surface if rim-to-pavement contact occurs. This is not to say inner tubes prevent debeading of the tire from the rim, however. Phase IV and VI testing demonstrated tire debeading can still occur when inner tubes are used, but because the tube usually remains inflated, the "cushioning" effect reduces the severity of the impact when the rim strikes the test surface. However, even with inner tubes, debeading of the outside front tire can be so severe that the inner tubes have ruptured, thus losing all air pressure. When this occurs, the damage to the test surface tends to be more severe than that produced during a test where the inner tubes remained intact.

NHTSA's experience on the test track has indicated that, generally speaking, a test for which rim contact occurs without inner tube failure predicts such a failure *will* occur if maneuver entrance speed is increased.

Example scenario: A Road Edge Recovery test performed at 40 mph (10 mph below the maximum speed) produces rim contact but does not rupture an inner tube. Does it make sense to proceed to 45 mph? Based on experience gained in Phase VI, it is very likely the 45 mph test would result in an inner tube blowout. Given that both tests were performed with entrance speeds less than the maximum, how much more useful is the information gained from the 45 mph test than that of the 40 mph test? Is it worth the additional damage to the test surface? Is it worth the potential damage to the test vehicle? It is important to recognize both of these tests would have likely resulted in tire blowouts had no inner tubes been installed.

For these reasons, the authors recommend any test series for which rim-to-pavement contact is made be terminated. Such contact does not have to be so severe that the inner tube is ruptured and inflation pressure is lost. If rim-to-pavement contact is observed during tests performed with left-right steering, the authors recommend right-left tests not be performed (left-right tests always precede those performed with right-left steering).

9.2 How should rim contact and/or tire debeading be reported (presented to the public)?

NHTSA's current New Car Assessment Program (NCAP) ratings are presented in tabular form. These tables include crash test based rating and SSF-based rollover resistance ratings. Perusal through the information contained in the various cells reveals some contain a rating and/or important supplemental information. For example, some crash tests have produced undesirable test outcomes that cannot be adequately represented with the rating scheme alone. In such cases, the appropriate cell not only contains a rating that reflects the likelihood the collision would have resulted in a serious injury (i.e., an injury requiring immediate hospitalization and that may be life threatening), but also a text-based description of other relevant safety concerns (e.g., "High Likihood of Pelvic Injury"). If a rating cannot be assigned to a particular cell for some reason, text-based information may also be used to explain to the public why the rating cannot be presented (e.g., "Seat Too Small").

When presenting the dynamic rollover resistance test rating of a vehicle, a similar technique may be able to be used to report rim-to-pavement contact made during a test that does not also produce two-wheel lift. In this situation, no [dynamic] rollover resistance rating can be assigned, as the test series must be terminated for the reasons discussed in Section 5.1. However, the fact that the vehicle was indeed tested should be acknowledged, and the authors believe the public would be interested in learning why no [dynamic] rollover resistance rating was assigned. For this reason the authors recommend the text "Test Terminated Due To Rim-To-Pavement Contact" be used to report such occurrences in the NCAP rating summary table.

If rim-to-pavement contact occurs during a test for which two-wheel lift occurred, both results should be reported. In this case, the authors recommend the text "Rim-To-Pavement Contact" be used to supplement the [dynamic] rollover resistance rating assigned to the vehicle.

9.3 How should the Multi-Passenger configuration be defined?

The authors recommend the Maximum Occupancy configuration used in Phase VI be replaced with the Multi-Passenger configuration. A formal definition of this configuration is presented in this section. The Multi-Passenger Configuration includes all elements of the Nominal Load Configuration plus ballast in the form of water dummies. Water dummies are installed as follows:

For vehicles with three or more designated rear seating positions, three 175 lb water dummies are used. The water dummies shall be positioned on the rear seats (second seating row) closest to driver and front passenger seats (first seating row). If there are only two seating positions in the second seating row, the third water dummy shall be placed in the center of the third seating row, provided it is a designated seating position, as shown in Figure A.17.

For vehicles with two designated rear seating positions, two 175 lb water dummies shall be positioned in the rear seats, as shown in Figure A.18.

For pickups with only front designated seating positions, three 175 lb water dummies will be used. The water dummies shall be positioned behind the cab in a manner that emulates a second seating row. If it is not possible to fit three water dummies directly behind the cab, the third water dummy shall be placed in the center of a simulated third seating row, as shown in Figure A.19.

For pickups with two seating rows, three 175 lb water dummies will be used. If the second seating row includes three designated seating positions, each water dummy shall be placed in these positions. If the second seating row includes two designated seating positions, two 175 lb water dummies shall be positioned in the second seating row of the cab, and the third water dummy shall be positioned behind the cab in a manner that emulates the center seating position of a third seating row, as shown in Figure A.20.

For all vehicles, if the Multi-Passenger Configuration results in the vehicle exceeding its Gross Vehicle Weight Rating (GVWR) and/or rear Gross Axle Weight Rating (GAWR), the weight of each dummy will be equally reduced until the GVWR and/or rear GAWR are no longer exceeded. The weight of the water dummies shall not be reduced if only the front GAWR is exceeded and the front axle weight does not exceed the front GAWR by more that 50 pounds, i.e., if the Multi-Passenger Configuration results in the vehicle exceeding its front GAWR, and its GVWR and/or rear GAWR, the weight of each dummy will be equally reduced until the GVWR and rear GAWR are no longer exceeded and the front GAWR is not exceeded by more that 50 pounds.

For non-pickup truck vehicles with only front designated seating positions, the Multi-Passenger Configuration is omitted from the test matrix. Only the Nominal Load configuration is used.

10.0 CONCLUSIONS

The findings presented in this report result from Phases VI and VII of NHTSA's Light Vehicle Rollover Research Program. Phase VI of this program was focused on determining the rollover resistance of a substantial number of vehicles. This was experimentally determined using the test maneuvers and procedures developed during Phases IV and V of the Light Vehicle Rollover Research Program. A broad range of twenty-six light vehicles was evaluated using one Characterization maneuver and two Rollover Resistance maneuvers capable of inducing on-road, untripped rollover. Up to two load configurations per vehicle were used.

The Phase VI vehicle fleet was comprised of nine SUVs, six pick-ups, five minivans, and six passenger cars. The vehicles were selected on the basis of vehicle classification, known single-vehicle rollover crash data, and SSF. Most of the vehicles were used; some had been previously used by NHTSA in other programs. Three vehicles were new.

Characterization maneuvers are used to provide vehicle-specific data for some fundamental performance metrics. Such maneuvers are not intended to produce two-wheel lift. The only Characterization maneuver used in this study was the Slowly Increasing Steer maneuver. This maneuver was used to provide the data required to calculate the handwheel steering angles of the two Rollover Resistance maneuvers used in Phase VI, the NHTSA J-Turn and NHTSA Road Edge Recovery. At the conclusion of Phase IV, NHTSA believed these maneuvers were good enough that they could be used by the Government for either regulation or consumer information.

Of the twenty-six vehicles evaluated in Phase VI, ten produced two-wheel lift. The only vehicle for which two-wheel lift was observed during each of the four Rollover Resistance Maneuver / load configuration combinations was the Acura SLX.

The most common tip-up scenario (for four of the ten vehicles; the Chevrolet Blazer, Mitsubishi Montero, Ford Ranger 4x4, and Ford Aerostar) was lift during the Maximum Occupancy J-Turn, Nominal Load Road Edge Recovery, and Maximum Occupancy Road Edge Recovery maneuvers.

Three vehicles, the Chevrolet Tracker, Ford Explorer XLS, and Toyota 4Runner, only experienced two-wheel lift during Road Edge Recovery tests performed in the Maximum Occupancy configuration.

The Chevrolet Astro was the only vehicle that experienced two-wheel lift during J-Turn and Road Edge Recovery tests performed in the Maximum Occupancy configuration only (i.e., no tip up occurred during tests performed with Nominal Load).

Steering divergences were observed during J-Turns and Road Edge Recovery maneuvers performed with some vehicles. Although these divergences affected the linearity of the handwheel steering angle ramps used for the affected vehicles, the authors do not believe their presence compromised maneuver severity or two-wheel lift repeatability. Furthermore, the authors believe the maximum torque capacity of the steering machine (36.9 lbf-ft) is able to adequately execute J-Turn or Road Edge Recovery maneuvers. Modifications designed to increase the maximum torque capacity of the steering machine are not deemed necessary.

The substantial number of diverse test vehicles used in Phase VI allowed NHTSA to realize maneuver severity may be better optimized if some minor adjustments to the test procedure were implemented. It was for this reason Phase VII of NHTSA's Light Vehicle Rollover Research Program was performed. Items addressed in Phase 7 included an improved definition of the Maximum Occupancy load configuration, a decision of how best to report the occurrence of rim-to-pavement contact and/or debeading in the consumer information program, and an evaluation of the concept of manipulating handwheel scalars to improve Rollover Resistance Maneuver severity.

Tests performed with the Multi-Passenger configuration were used to examine how the use of a standard number of simulated occupants can affect the performance of two minivans with known rollover resistance (i.e., measured in Phase VI). When compared to the results obtained during Phase VI Maximum Occupancy tests, the data indicate use of only three water dummies improved the rollover resistance of the Chevrolet Astro during J-Turn and Road Edge Recovery testing. Conversely, the Multi-Passenger configuration slightly degraded the rollover resistance of the Ford Aerostar from that observed during Maximum Occupancy tests. The disparity of the input conditions (placement of the water dummies) and test outcome (improved or degraded rollover resistance when compared to the Maximum Occupancy results), indicate the Multi-Passenger configuration affects vehicles differently, even if they are members of the same classification category (i.e., minivan).

Use of the Multi-Passenger configuration degraded the rollover resistances of the Astro and Aerostar from that observed during Nominal Load tests. Therefore, use of both configurations will allow NHTSA to effectively evaluate the rollover resistance of vehicles at two severity levels. Also, the face validity of the Multi-Passenger loading surpasses that of the Maximum Occupancy configuration. Most passenger vehicles are not typically loaded to the limit of their seating capacity. While not necessarily "worst-case," Multi-Passenger loading is far more likely to be realized during actual driving on public roadways.

The reduction of steering scalars can improve the effectiveness of NHTSA's Rollover Resistance maneuvers. However, use of steering scalars less than 6.0 during J-Turn testing does not appear to be advantageous. For two of the four vehicles evaluated with reduced steering scalars (the Ford Aerostar and Ford Ranger 4x4), scalars of 6.0 and/or 7.0 were able to produce two-wheel lift, while scalars of 5.0 and 8.0 were not. These results are encouraging since changes to the existing J-Turn test procedure can easily incorporate the use of lesser scalars to promote maximum maneuver severity.

In the case of the Road Edge Recovery maneuver, the use of steering scalars less than 5.5 do not appear to be advantageous. In Phase VII, none of the four vehicles produced two-wheel lift during Road Edge Recovery tests performed with steering inputs based on scalars of 3.5 (Astro and Ranger 4x2) or 4.5. In the case of the Aerostar, steering inputs based on scalars of 5.5 and 6.5 were able to produce two-wheel lift. Only the use of steering inputs based on a scalar of 6.5 was able to produce two-wheel lift with the Ranger 4x4. As with the J-Turn, changes to the existing Road Edge Recovery test procedure can easily incorporate the use of a lesser scalar to promote maximum maneuver severity.

A Ford Explorer 4x2 was used to assess whether increasing steering scalars can improve J-Turn and Road Edge Recovery maneuver severity. Phase VII results indicate that the use of large handwheel angles does not necessarily insure maneuver severity is maximized. Tests performed with the Explorer 4x2 indicate it is possible for handwheel angles calculated with small steering scalars to produce peak yaw rates, lateral accelerations, and roll angles in excess of those produced with larger scalars.

For each vehicle evaluated in Phase VII, reducing the magnitude of the handwheel steering scalars increased Road Edge Recovery dwell time duration. Similarly, increasing the scalar magnitude reduced dwell time duration. In every case, a steering scalar reduction of 1.0 was great enough that there was no overlapping in the ranges of dwell times associated with each scalar. This indicates a reduction of 1.0 is great enough to significantly affect how the vehicle will respond to a maneuver. If maximum roll angle is produced prior to completion of the initial steer during a Road Edge Recovery test, Phase VII results indicate a scalar reduction of 1.0 is generally enough to remedy the condition.

The authors recommend that any test series for which rim-to-pavement contact is made be terminated, even if two-wheel lift had not yet been observed. Such contact does not have to be so severe that the inner tube is ruptured and inflation pressure is lost. If rim-to-pavement contact occurs, the authors believe the event should be reported as supplementary information, presented to the public along with that vehicle's NCAP rollover rating.

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9. American Society for Testing and Materials. "Standard Specification for Standard Rib Tire for Pavement Skid-Resistance Tests," 1996 Annual Book of ASTM Standards, Section 4 – Construction, Vol. 04.03 – Road and Paving Materials; Vehicle-Pavement Systems, 1996.

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11. "NHTSA Setup Procedures For Wheel Lift Sensors – A Brief Overview," Docket Submission NHTSA-9663-81, March 2003.

12. Heitzman, E.J., and Heitzman, E.F., "A Programmable Steering Machine for Vehicle Handling Tests," SAE Paper 971057, SAE SP-1228, February 1997.

13. Heitzman, E.J., and Heitzman, E.F., "The ATI Programmable Steering Machine," Automotive Testing, Inc. Technical Report, March 1997.

14. SAE J266, Surface Vehicle Recommended Practice, "Steady-State Directional Control Test Procedures For Passenger Cars and Light Trucks," 1996.

APPENDIX

Table A.1. Phase VI and VII Overall Tire Summary (Sorted By Baseline SSF In Descending Order, Per Vehicle Class).

Vehicle	Size	Load Index / Speed Rating	Original Equipment		Phase VI and VII		Inflation Pressure			
			Make	Model	Make	Model	Nominal / Max Occupancy		Rear Load (GVWR)	
							Front	Rear	Front	Rear
1998 Honda CR-V	P205/70R15	95S	Bridgestone	Dueler H/T 684	Bridgestone	Dueler H/T 684	26	26	26	26
1998 Chevrolet Tracker	P205/75R15	97S	Goodyear	Wrangler RT/S	Goodyear	Wrangler RT/S	23	23	23	23
1997 Jeep Cherokee Sport	P225/75R15	105S	Goodyear	Wrangler RT/S	Goodyear	Wrangler RT/S	33	33	33	33
2001 Toyota 4Runner	P265/70R16	111S	Bridgestone	Dueler H/T 689	Bridgestone	Dueler H/T 689	32	32	32	32
1996 Acura SLX	P245/70R16	106S	Bridgestone	Dueler 684	Bridgestone	Dueler 684	30	35	30	35
2001 Ford Explorer XLS	P235/75R15	105S	Goodyear	Wrangler RS-A	Goodyear	Wrangler RT/S	26	26	26	26
2001 Ford Explorer Sport	P235/75R15	105S	Goodyear	Wrangler RT/S	Goodyear	Wrangler RT/S	30	30	30	30
2001 Chevrolet Blazer	P235/70R15	102S	Uniroyal	Laredo	Uniroyal	Laredo	32	32	32	32
1995 Mitsubishi Montero	P235/75R15	105S	Michelin	Radial XCH4	Michelin	LTX-MS	26	35	26	35
1992 Ford F-150	P215/75R15	100S	Goodyear	Invicta	Goodyear	Integrity	35	35	35	35
1994 Chevrolet C1500	P235/75R15	105S	Uniroyal	Tiger Paw XTM	Uniroyal	Tiger Paw XTM	32	35	32	35
1997 Ford F-150	P235/70R16	104S	BF Goodrich	Long Trail T/A	BF Goodrich	Long Trail T/A	32	35	32	35
1995 Chevrolet K1500	LT225/75R16	Load Range C	General	Ameri 550AS	General	Ameri 550AS	50	50	50	50
1997 Ford Ranger 4x2	P225/70R14	98S	Firestone	Wilderness HT	Firestone	Wilderness HT	35	35	35	35
1997 Ford Ranger 4x4	P235/75R15	105S	Firestone	Wilderness AT	Firestone	Wilderness AT	30	35	30	35
1998 Plymouth Voyager	P205/75R14	95S	Goodyear	Conquest	Goodyear	Conquest	35	35	35	35
1995 Ford Windstar GL	P205/70R15	95S	Michelin	XW4	Michelin	XW4	35	35	35	35
1994 Dodge Caravan	P195/75R14	92S	Goodyear	Invicta GAL	Goodyear	Integrity	35	35	35	35
1995 Chevrolet Astro	P215/75R15	100S	General	AmeriTech	General	AmeriTech ST	35	35	35	35
1993 Ford Aerostar[1]	P215/75R14	98S	Michelin	XW4	General	Ameri G4S	32	35	32	35
2002 Chevrolet Corvette	P245/45ZR17 (F) P275/40ZR18 (R)	89Y (F) 94Y (R)	Goodyear	Eagle F1 GS (EMT)	Goodyear	Eagle F1 GS (EMT)	30	30	30	30
1992 Honda Civic LX	P175/70R13	82S	Goodyear	Invicta GLR	Dunlop	SP40	32	32	32	32
1994 Ford Taurus	P205/65R15	92T	General	AmeriTech ST	General	Ameri G4S	35	35	35	35
1993 Chevrolet Caprice Classic	P215/75R15	100S	General	AmeriTech ST	General	AmeriTech ST	30	30	30	30
1997 Chevrolet Metro	P155/80R13	79S	Goodyear	Invicta GL	Goodyear	Invicta GL	32	32	32	32
1991 Chevrolet Cavalier	P185/75R14[1] P195/70R14[2]	89S	General	AmeriTech ST	Goodyear	Conquest	35	35	35	35

[1] Aerostar Original Equipment (OE) tires were no longer in production, and the OE manufacturer did not produce a contemporary equivalent in the correct size.
[2] Installed as OE.
[2] Size recommended by vehicle and OE tire manufacturers, and used in Phase VI. The OE tire was no longer in production and no comparable tire in the OE size was available.

Table A.2. Test Vehicle Weight, C.G. Location, and Mass Moments of Inertia (Baseline, Sorted By SSF In Descending Order, Per Vehicle Class).

Vehicle	Weight (lbs)	C.G.			SSF	Mass Moments of Inertia		
		Longitudinal (in)	Height (in)	Lateral Offset (in)		Pitch (ft-lb-sec^2)	Roll (ft-lb-sec^2)	Yaw (ft-lb-sec^2)
1998 Honda CR-V	3371	46.63	25.03	-0.59	1.210	1826	431	1977
1998 Chevrolet Tracker	2625	39.87	24.26	-0.84	1.131	959	262	1044
1997 Jeep Cherokee Sport	3684	44.95	26.38	-0.91	1.102	1838	420	1993
2001 Toyota 4Runner	4239	48.57	27.07	-1.17	1.098	2437	463	2544
1996 Acura SLX	4467	52.13	27.33	-0.51	1.098	2758	572	2874
2001 Ford Explorer XLS	4446	51.38	27.10	-1.45	1.085	2611	497	2685
2001 Ford Explorer Sport	4057	47.55	27.37	-1.48	1.070	2161	466	2247
2001 Chevrolet Blazer	3998	49.10	26.63	-1.00	1.025	2273	429	2384
1995 Mitsubishi Montero	4655	57.55	29.35	-1.13	0.953	2859	581	2920
1992 Ford F-150	4397	56.53	26.50	-0.86	1.225	3638	479	3909
1994 Chevrolet C1500	4273	57.22	26.33	-1.06	1.219	3268	517	3579
1997 Ford F-150	4438	57.02	26.92	-0.86	1.212	3538	572	3774
1995 Chevrolet K1500	4856	53.45	27.74	-1.16	1.152	3645	548	3911
1997 Ford Ranger 4x2	3228	44.02	25.12	-1.85	1.136	1702	336	1821
1997 Ford Ranger 4x4	3723	43.22	27.08	-1.78	1.070	1922	382	2048
1998 Plymouth Voyager	3812	46.92	24.96	-1.34	1.273	2417	581	2609
1995 Ford Windstar GL	3943	46.72	25.34	-0.48	1.258	2757	593	2974
1994 Dodge Caravan	3616	47.03	25.82	-0.93	1.182	2207	475	2377
1995 Chevrolet Astro	4422	50.83	29.01	-1.11	1.126	2778	690	2938
1993 Ford Aerostar	3879	51.46	27.30	-1.21	1.117	2263	537	2389
2002 Chevrolet Corvette	3361	51.45	17.61	-0.55	1.749	1442	341	1637
1992 Honda Civic LX	2529	39.90	19.88	-1.09	1.462	1212	257	1360
1994 Ford Taurus	3407	37.63	21.08	-0.94	1.447	1845	363	2072
1993 Chevrolet Caprice Classic	4097	50.68	22.21	-0.55	1.406	2718	453	3022
1997 Chevrolet Metro	2057	35.41	20.37	-1.46	1.326	782	202	867
1991 Chevrolet Cavalier	2728	36.99	21.19	-0.88	1.310	1333	271	1474

Table A.3. Test Vehicle Weight, C.G. Location, and Mass Moments of Inertia (Nominal Load, Sorted By Baseline SSF In Descending Order, Per Vehicle Class).

Vehicle	Weight (lbs)	C.G.			SSF	Mass Moments of Inertia		
		Longitudinal (in)	Height (in)	Lateral Offset (in)		Pitch (ft-lb-sec^2)	Roll (ft-lb-sec^2)	Yaw (ft-lb-sec^2)
1998 Honda CR-V	3636	47.12	24.47	-0.58	1.238	2084	485	2279
1998 Chevrolet Tracker	2874	40.26	23.78	-0.52	1.154	1127	324	1257
1997 Jeep Cherokee Sport	4017	46.01	25.43	-0.85	1.143	2176	509	2382
2001 Toyota 4Runner	4481	47.44	26.47	-0.84	1.123	2611	559	2775
1996 Acura SLX	4798	52.56	26.58	-0.46	1.128	3090	640	3246
2001 Ford Explorer XLS	4758	51.32	26.41	-1.32	1.113	2960	558	3080
2001 Ford Explorer Sport	4341	48.00	26.90	-1.34	1.089	2397	523	2581
2001 Chevrolet Blazer	4352	49.38	25.81	-0.90	1.061	2579	523	2731
1995 Mitsubishi Montero	4961	57.74	28.56	-0.95	0.980	3198	650	3317
1992 Ford F-150	4641	56.26	26.10	-0.42	1.244	4013	557	4311
1994 Chevrolet C1500	4508	57.49	26.02	-0.78	1.234	3600	568	3938
1997 Ford F-150	4668	56.86	26.61	-0.75	1.226	3904	631	4205
1995 Chevrolet K1500	5080	53.89	27.36	-0.94	1.168	3960	614	4273
1997 Ford Ranger 4x2	3461	44.82	24.60	-1.70	1.159	1954	387	2117
1997 Ford Ranger 4x4	3972	44.46	26.58	-1.46	1.090	2230	437	2400
1995 Chevrolet Astro	4731	51.18	28.50	-1.03	1.147	3122	769	3328
1994 Dodge Caravan	3944	46.88	24.83	-0.74	1.229	2542	532	2766
1993 Ford Aerostar	4196	51.50	26.64	-0.90	1.144	2658	612	2839
1995 Ford Windstar GL	4253	47.11	24.70	-0.33	1.291	3208	671	3475
1998 Plymouth Voyager	4127	47.72	24.18	-1.19	1.314	2750	654	2998
2002 Chevrolet Corvette	3624	51.75	17.25	-0.33	1.786	1717	388	1952
1992 Honda Civic LX	2784	40.83	19.30	-0.79	1.507	1454	310	1647
1994 Ford Taurus	3683	38.61	20.60	-0.72	1.481	2186	421	2467
1993 Chevrolet Caprice Classic	4347	51.37	21.41	-0.42	1.458	2995	530	3353
1997 Chevrolet Metro	2320	36.26	19.53	-1.00	1.383	979	255	1104
1991 Chevrolet Cavalier	2950	38.15	20.40	-0.61	1.361	1528	319	1709

Table A.4. Test Vehicle Weight, C.G. Location, and Mass Moments of Inertia (Maximum Occupancy, Sorted By Baseline SSF In Descending Order, Per Vehicle Class).

Vehicle	Water Dummy Position	Weight (lbs)	C.G.			SSF	Mass Moments of Inertia		
			Longitudinal (in)	Height (in)	Lateral Offset (in)		Pitch (ft-lb-sec²)	Roll (ft-lb-sec²)	Yaw (ft-lb-sec²)
1998 Honda CR-V	Rear Seat (2[1])	3985	50.60	24.97	-0.45	1.213	2193	510	2395
1998 Chevrolet Tracker	Rear Seat (2)	3212	44.62	24.83	-0.54	1.105	1255	359	1371
1997 Jeep Cherokee Sport	Rear Seat (3)	4548	50.82	25.95	-0.77	1.120	2314	538	2550
2001 Toyota 4Runner	Rear Seat (3)	5041	52.02	27.45	-0.80	1.083	2775	579	2948
1996 Acura SLX	Rear Seat (3)	5327	56.06	27.74	-0.55	1.081	3214	677	3397
2001 Ford Explorer XLS	Rear Seat (3)	5286	55.27	27.25	-1.20	1.079	3116	584	3247
2001 Ford Explorer Sport	Rear Seat (2)	4696	50.97	27.47	-1.32	1.067	2561	554	2684
2001 Chevrolet Blazer	Rear Seat (3)	4876	53.55	26.49	-0.93	1.034	2741	551	2884
1995 Mitsubishi Montero	Center Seat (3), Rear Seat (2[2])	5657	63.55	29.58	-0.75	0.946	3489	698	3618
1992 Ford F-150	"Center Seat" (3[2]), "Rear Seat" (3[2]).	5425	64.20	26.65	-0.70	1.219	4505	635	4813
1994 Chevrolet C1500	"Center Seat" (3), "Rear Seat" (3)	5692	68.38	27.38	-0.65	1.173	4302	644	4613
1997 Ford F-150	"Center Seat" (3), "Rear Seat" (3)	5838	68.03	28.34	-0.58	1.151	4682	693	4974
1995 Chevrolet K1500	"Center Seat" (3), "Rear Seat" (3)	6080	62.65	28.86	-0.77	1.108	4580	660	4869
1997 Ford Ranger 4x2	"Rear Seat" (2)	3880	50.04	25.39	-1.61	1.124	2147	409	2295
1997 Ford Ranger 4x4	"Rear Seat" (2)	4365	49.18	27.53	-1.35	1.052	2438	466	2596
1998 Plymouth Voyager	Center Seat (2), Rear Seat (3)	5012	57.50	25.51	-1.51	1.246	3280	705	3507
1995 Ford Windstar GL	Center Seat (2), Rear Seat (3)	5115	57.33	26.09	-0.60	1.222	3813	724	4071
1994 Dodge Caravan	Center Seat (2), Rear Seat (3)	4819	56.80	26.04	-1.04	1.172	3046	627	3266
1995 Chevrolet Astro	Center Seat (3), Rear Seat (3)	5785	58.71	30.53	-1.48	1.070	3538	852	3737
1993 Ford Aerostar	Center Seat (2[2]), Rear Seat (3)	4940	59.37	28.50	-1.04	1.070	3088	660	3263
1992 Honda Civic LX	Rear Seat (2[1])	3137	46.07	19.34	-0.68	1.503	1601	324	1788
1994 Ford Taurus	Rear Seat (3)	4210	44.73	20.56	-0.81	1.484	2424	447	2704
1993 Chevrolet Caprice Classic	Rear Seat (3)	4878	56.29	21.45	-0.43	1.456	3199	562	3551
1997 Chevrolet Metro	Rear Seat (2[2])	2624	43.87	19.08	-0.94	1.416	1213	258	1355
1991 Chevrolet Cavalier	Rear Seat (2[1])	3304	43.07	20.53	-0.47	1.352	1663	336	1851

[1]Although the vehicle had three designated rear seating positions, only two full sized-water dummies were able to be used.

[2]Simulated 5th percentile female water dummies were used in these seats.

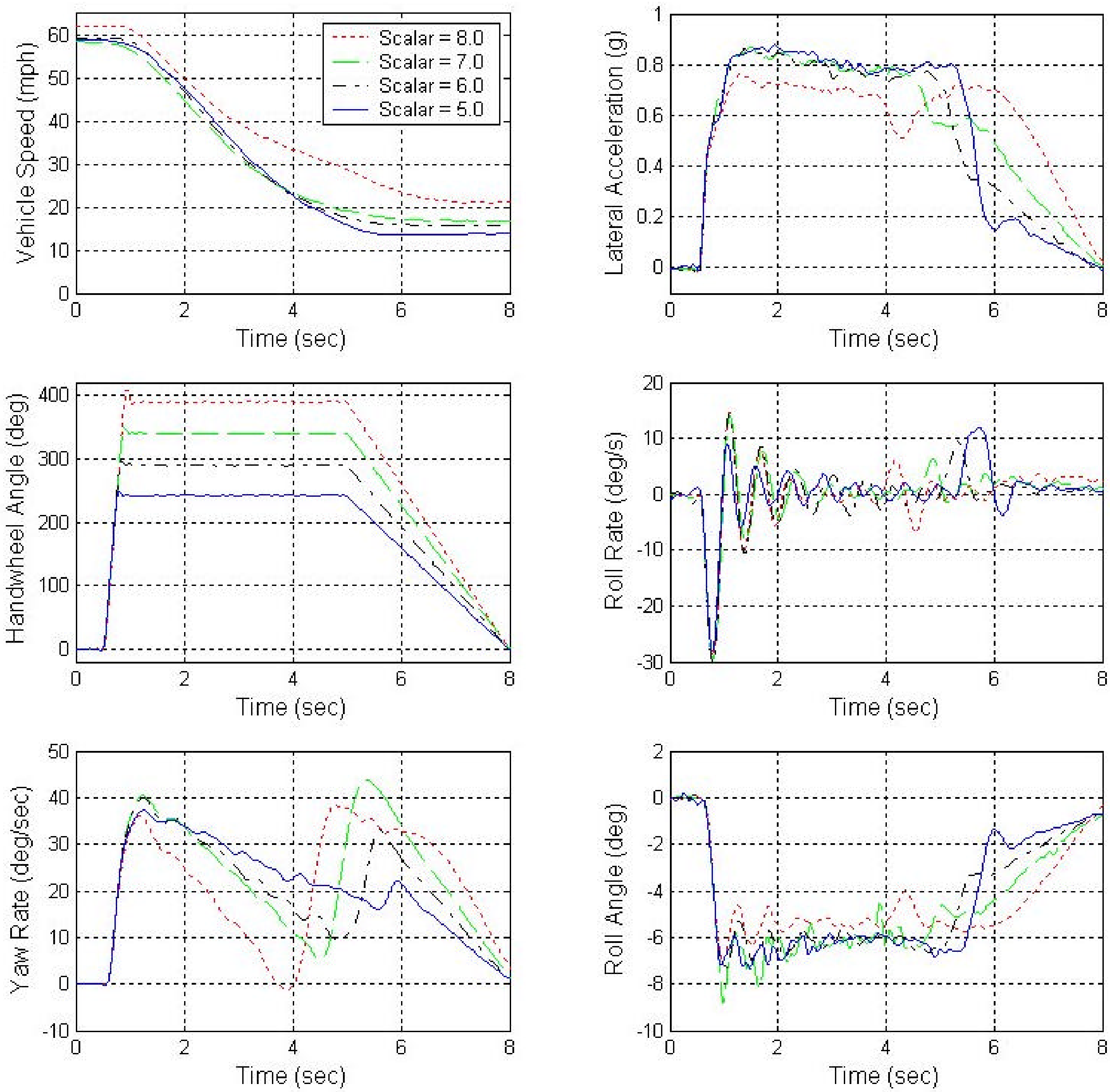

Figure A.1. Right-steer J-Turn tests performed with a 1995 Chevrolet Astro using four steering scalars.

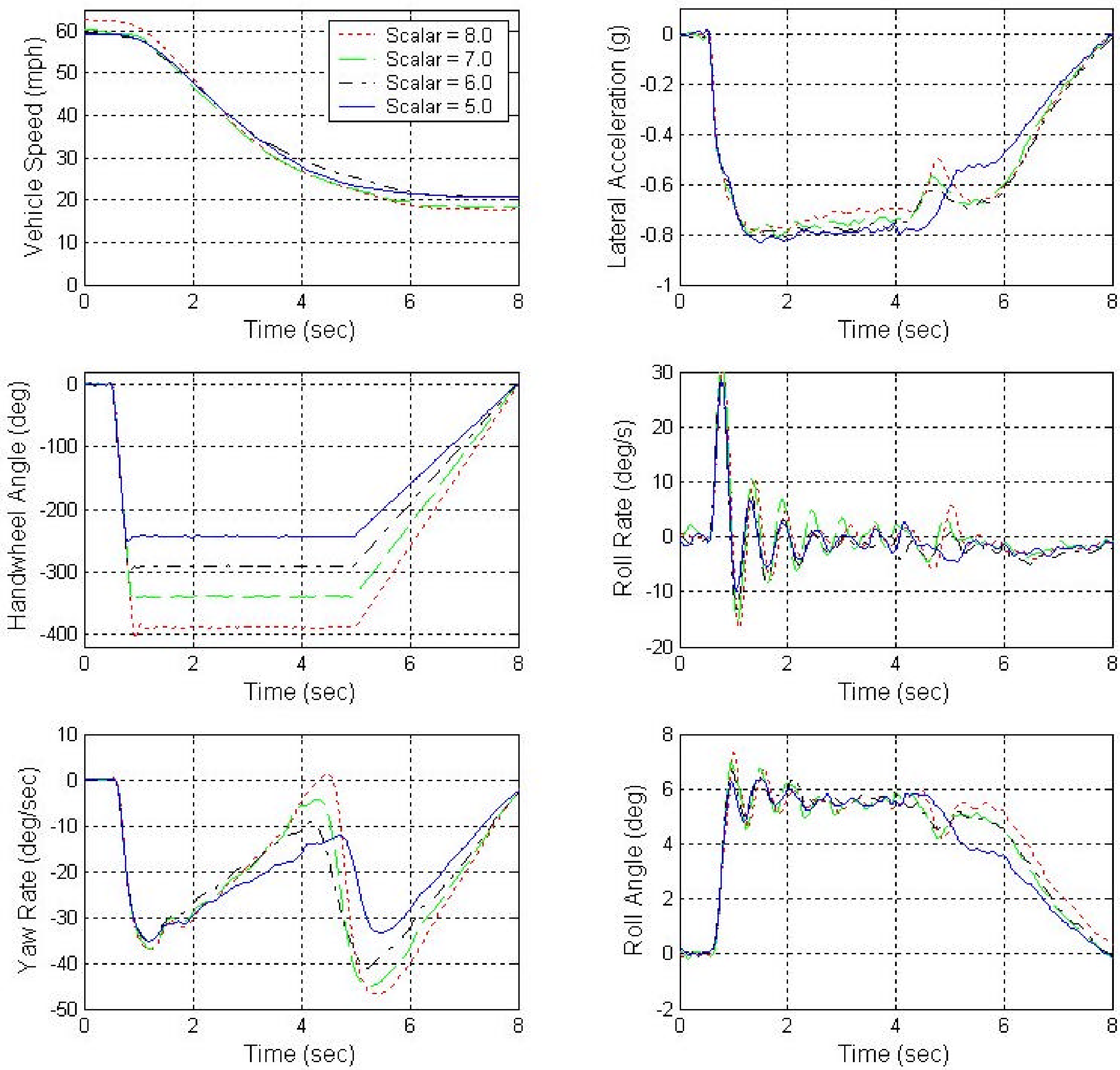

Figure A.2. Left-steer J-Turn tests performed with a 1995 Chevrolet Astro using four steering scalars.

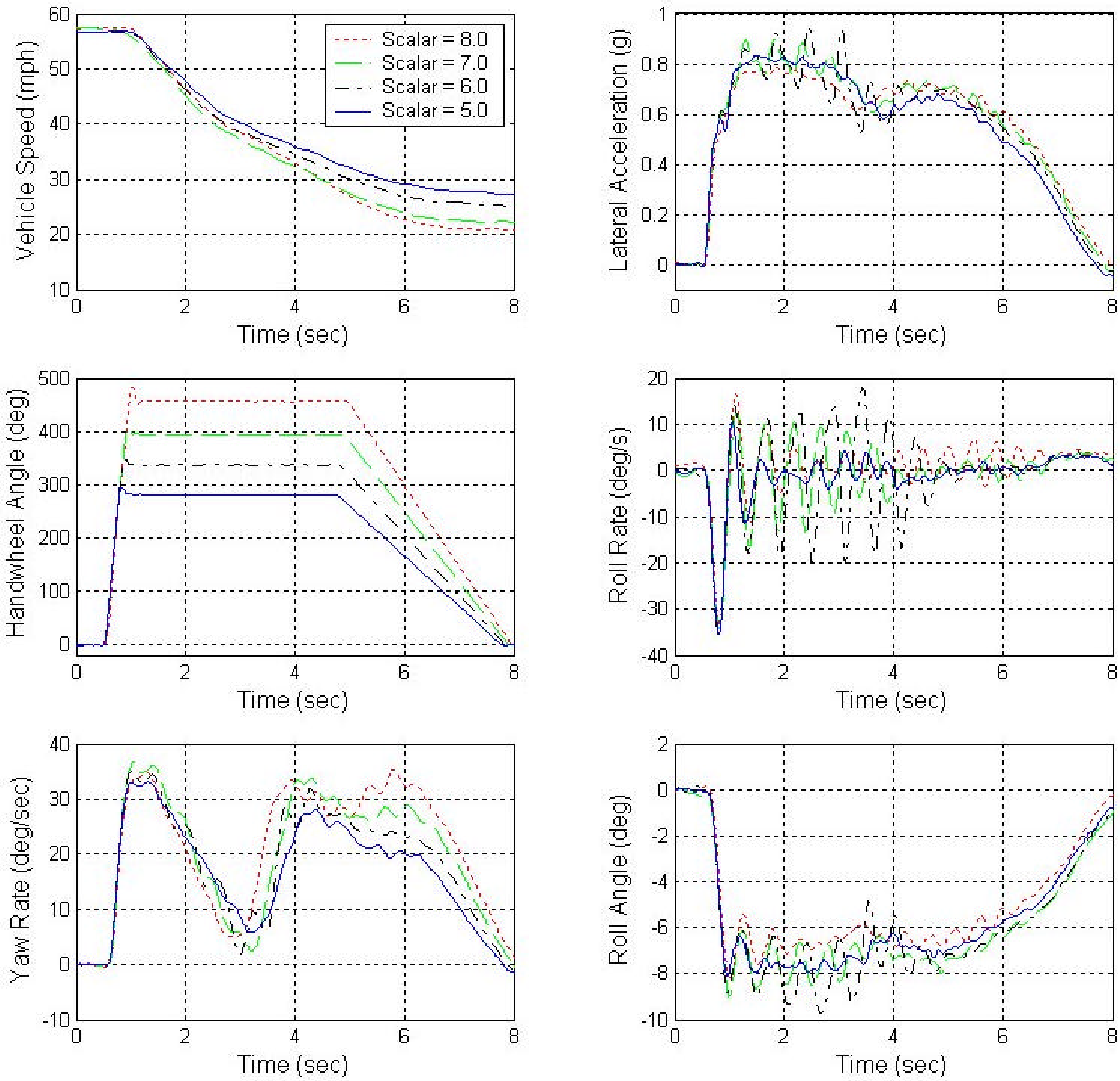

Figure A.3. Right-steer J-Turn tests performed with a 1993 Ford Aerostar using three steering scalars.

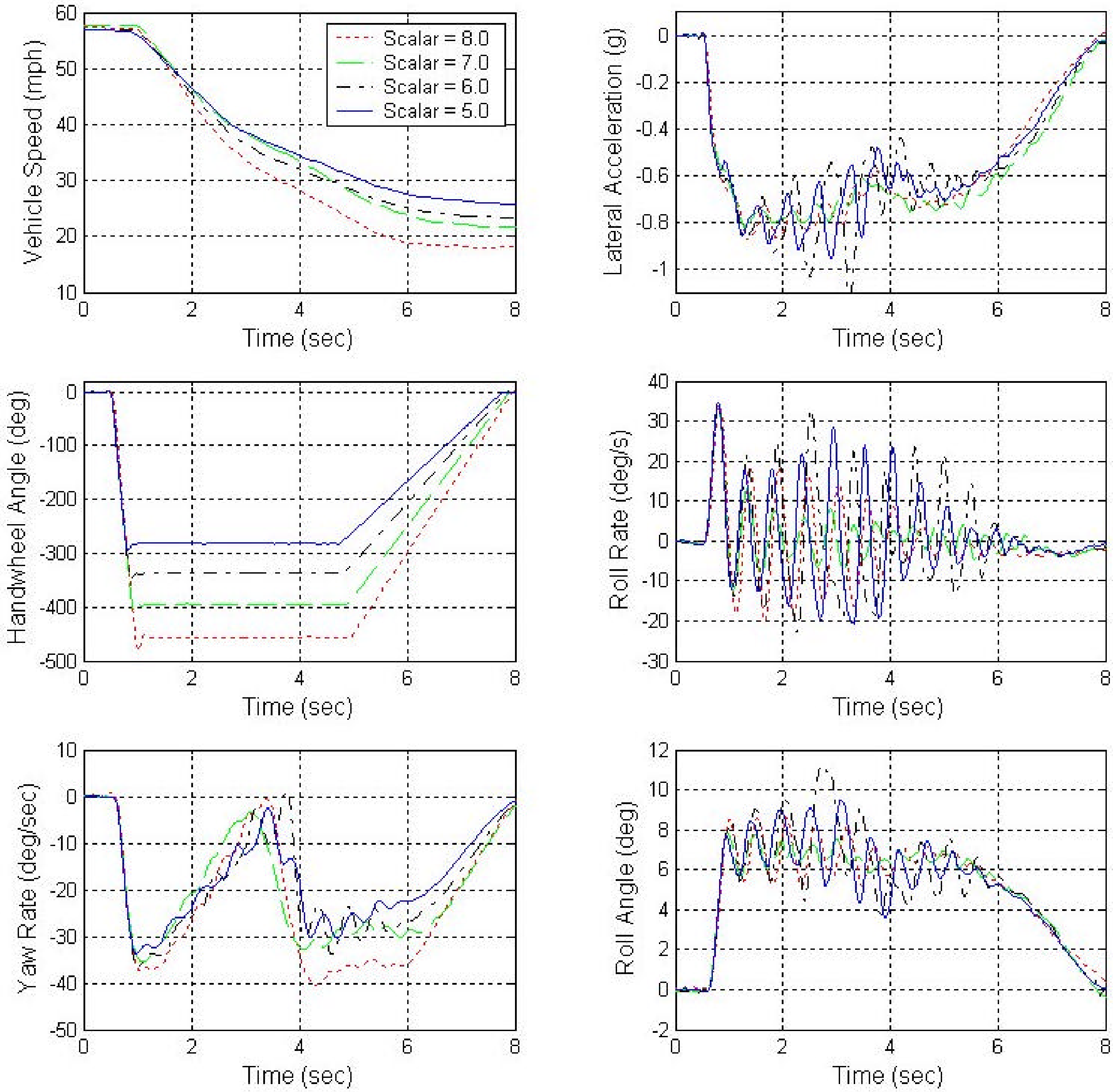

Figure A.4. Left-steer J-Turn tests performed with a 1993 Ford Aerostar using three steering scalars.

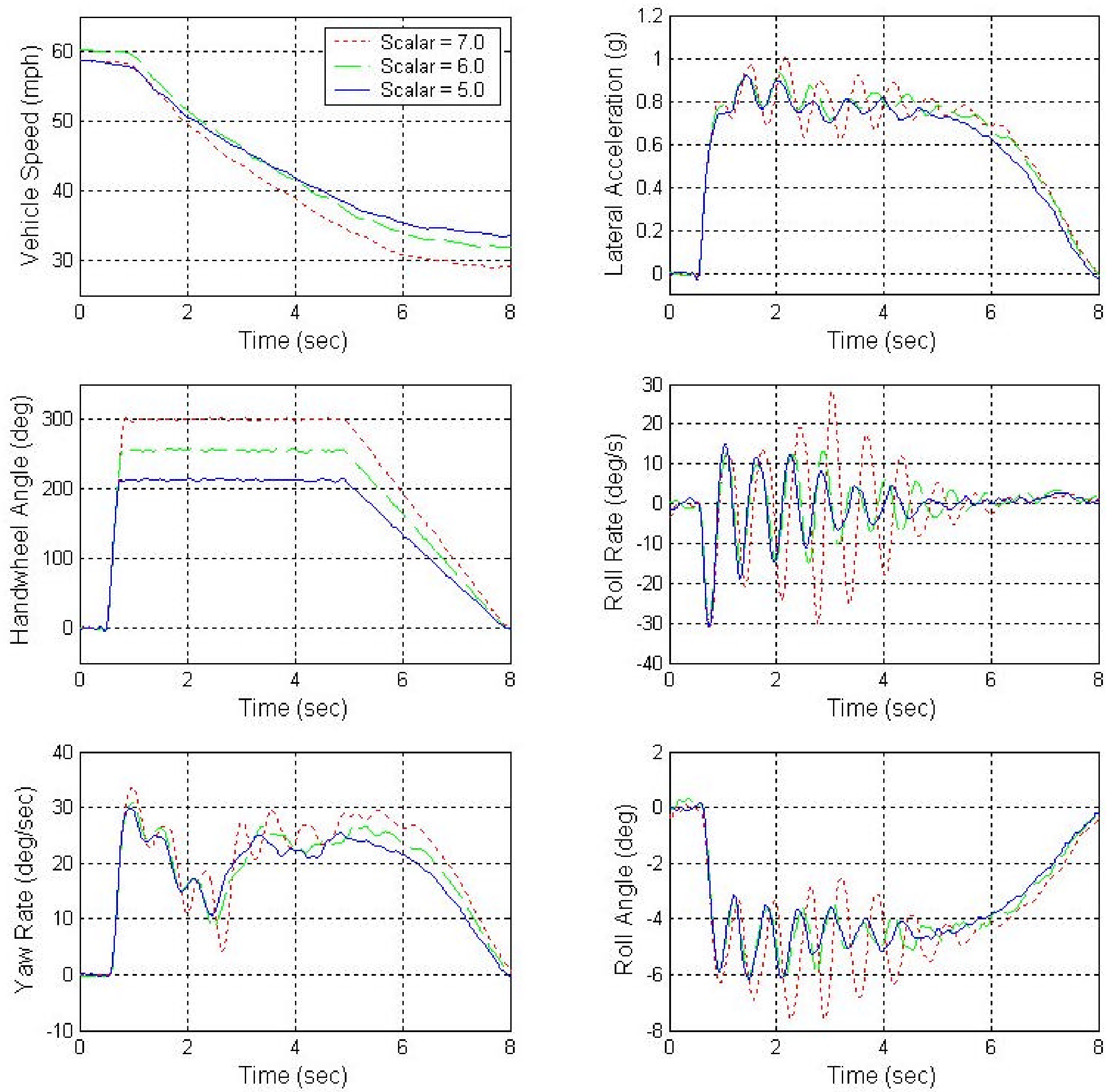

Figure A.5. Right-steer J-Turn tests performed with a 1997 Ford Ranger 4x2 using three steering scalars.

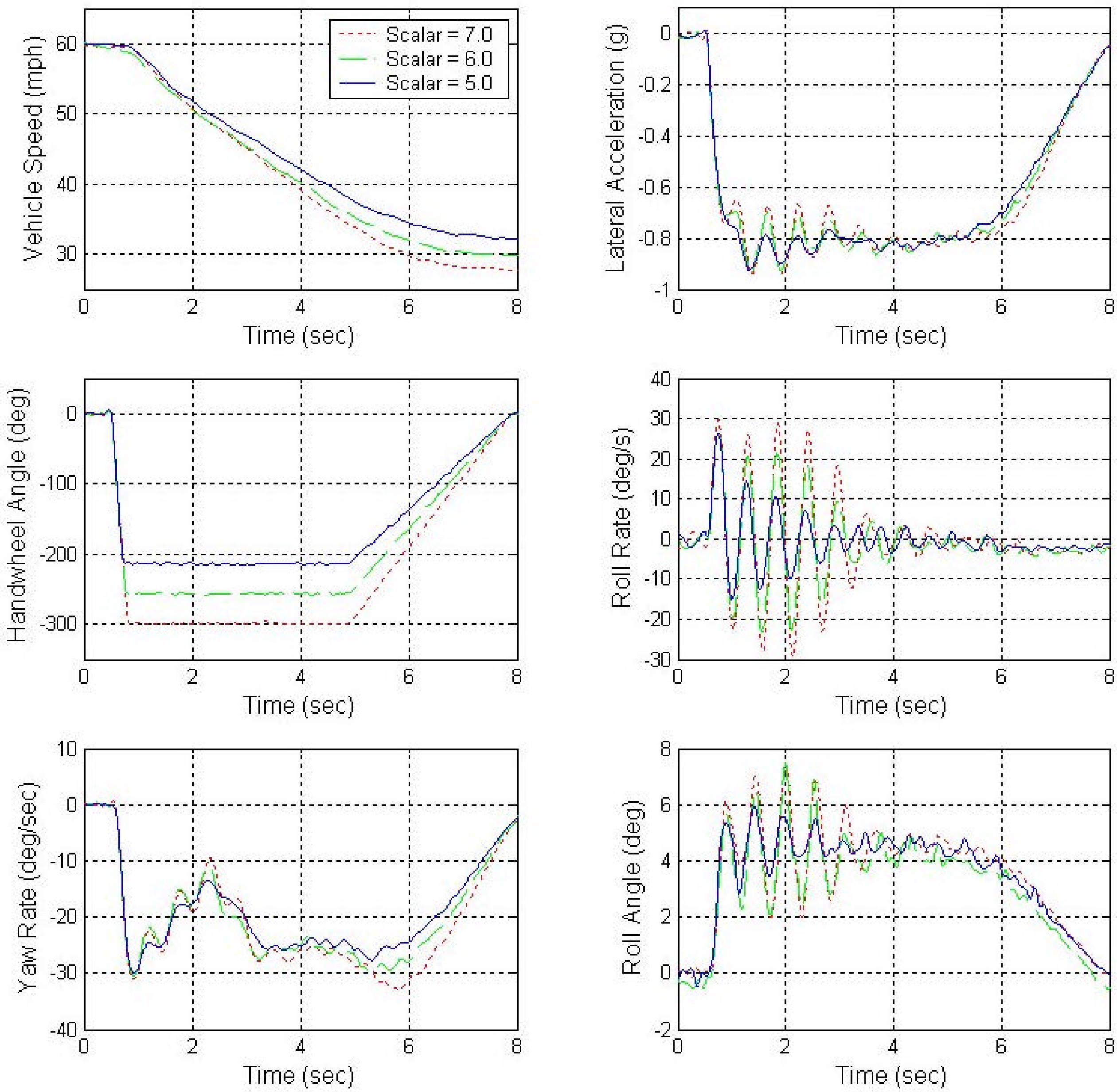

Figure A.6. Left-steer J-Turn tests performed with a 1997 Ford Ranger 4x2 using three steering scalars.

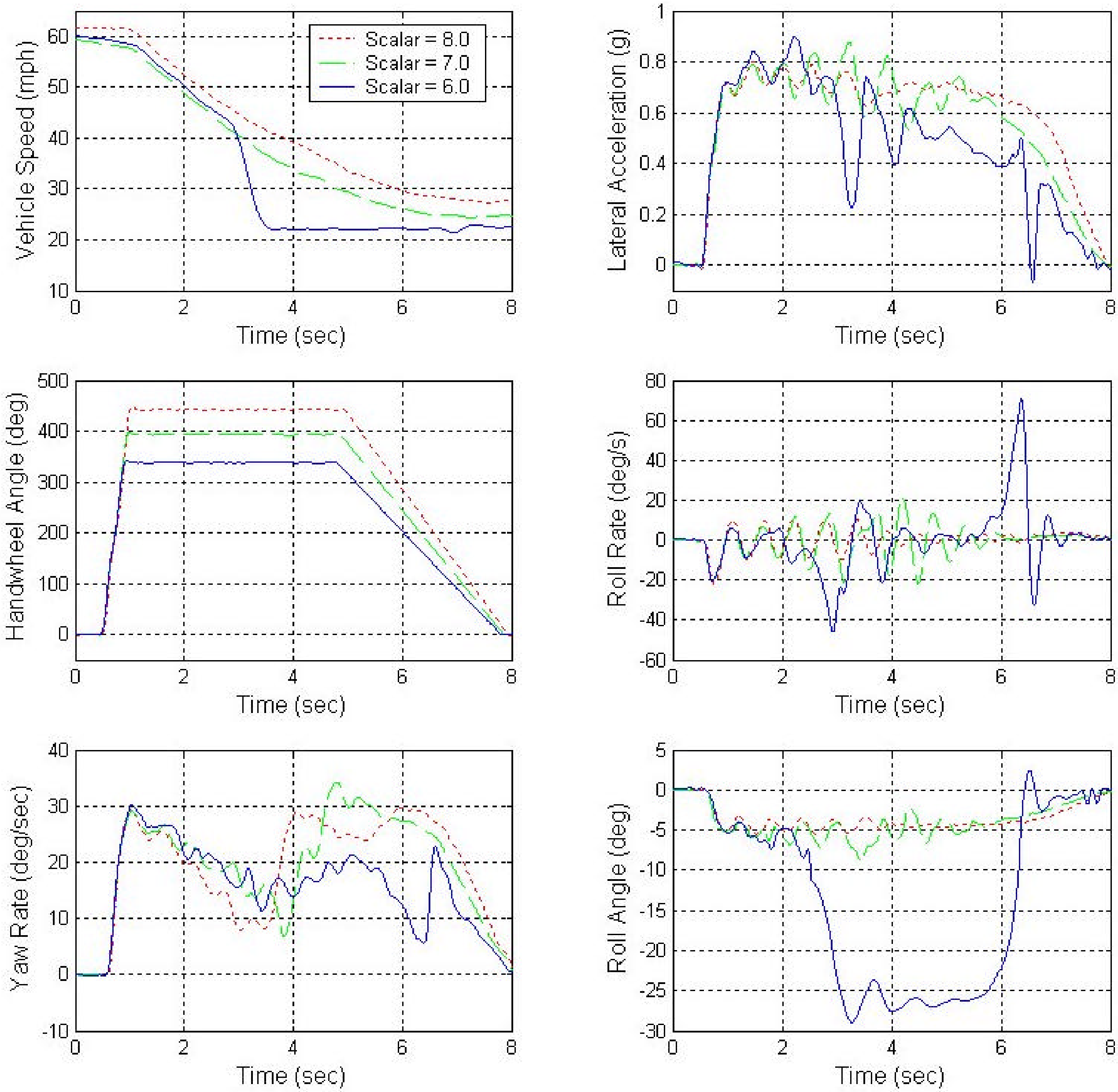

Figure A.7. Right-steer J-Turn tests performed with a 1997 Ford Ranger 4x4 using three steering scalars.

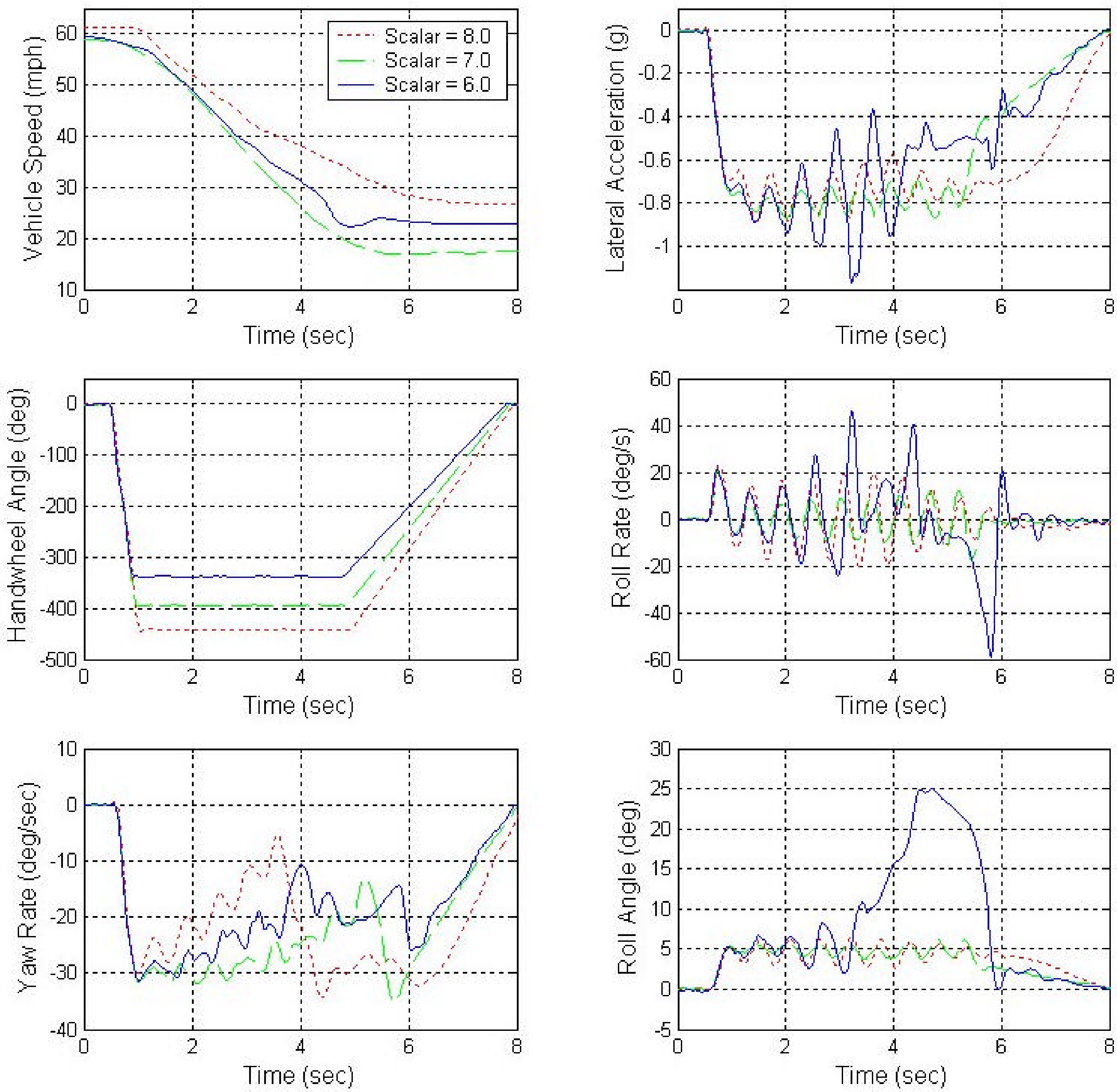

Figure A.8. Left-steer J-Turn tests performed with a 1997 Ford Ranger 4x4 using three steering scalars.

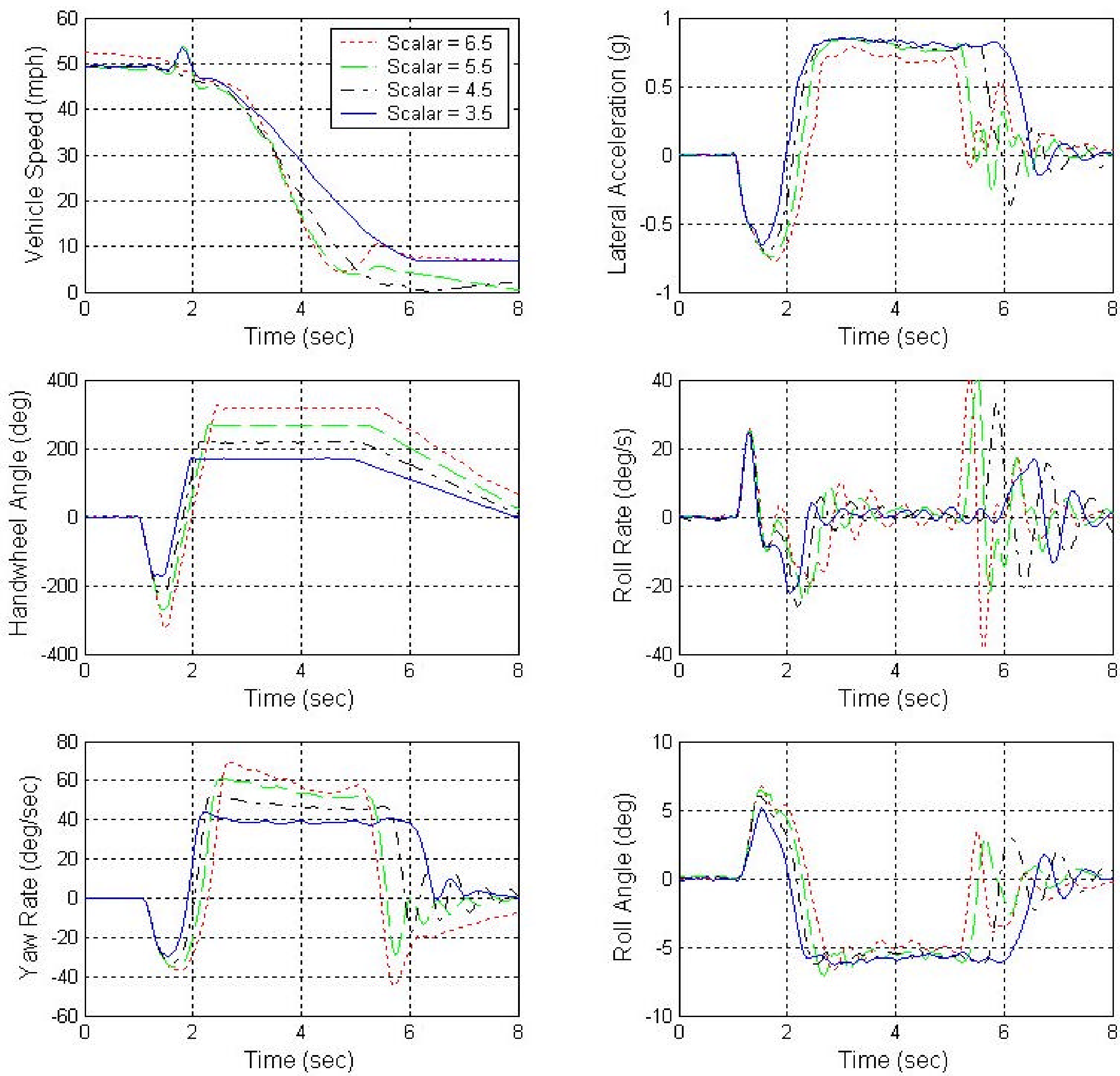

Figure A.9. Left-Right Road Edge Recovery tests performed with a 1995 Chevrolet Astro using four steering scalars.

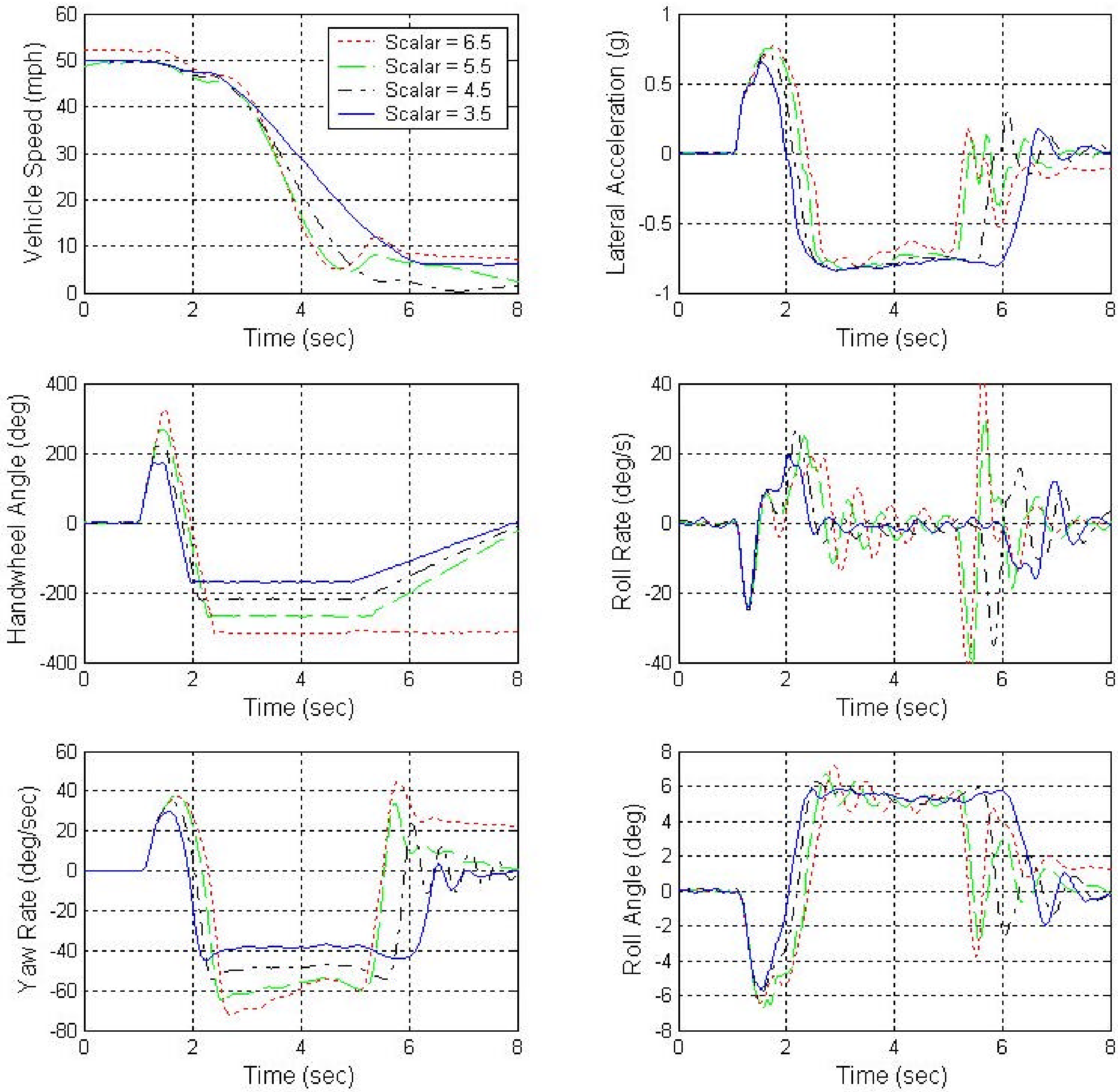

Figure A.10. Right-Left Road Edge Recovery tests performed with a 1995 Chevrolet Astro using four steering scalars.

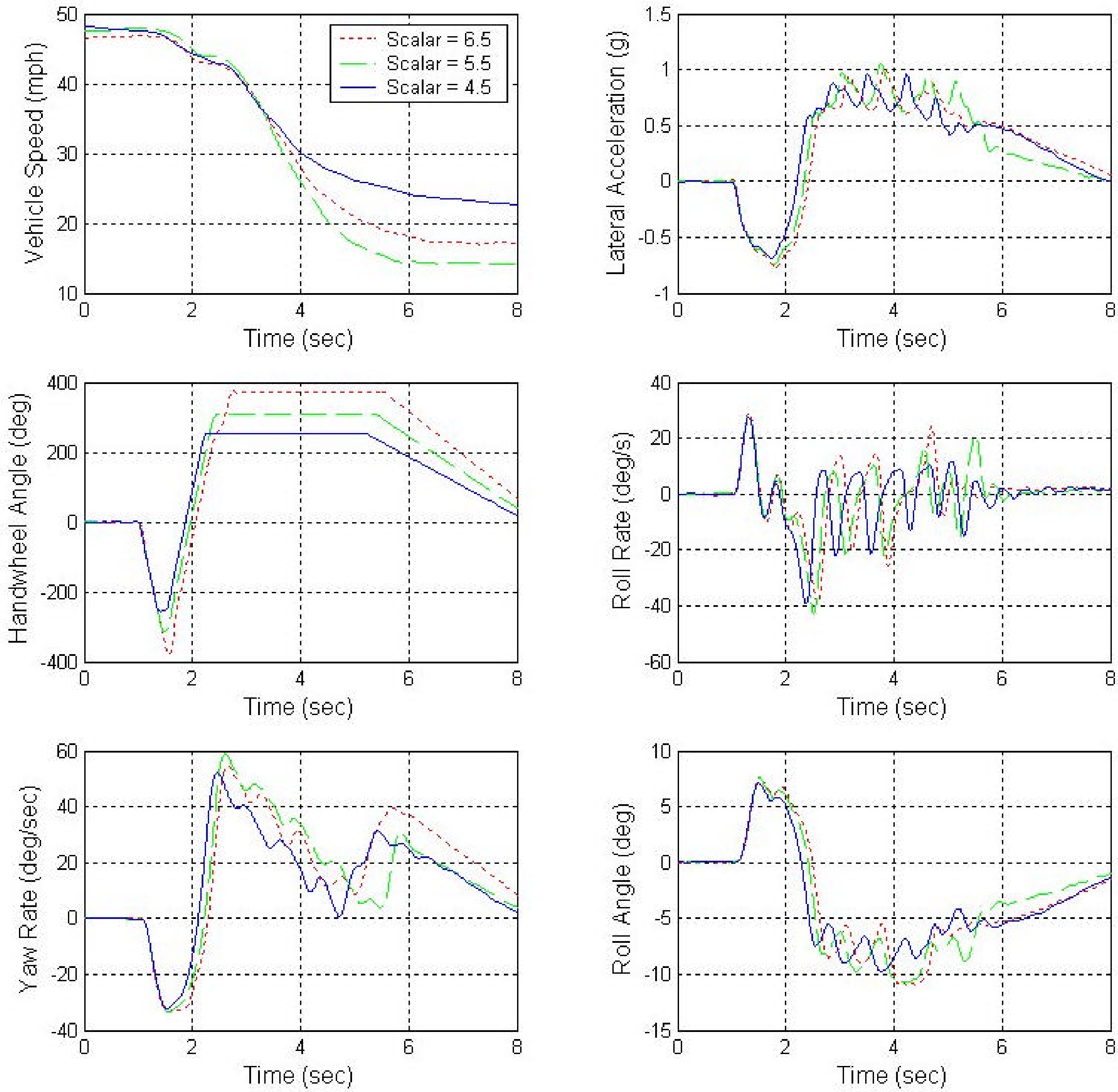

Figure A.11. Left-Right Road Edge Recovery tests performed with a 1993 Ford Aerostar using three steering scalars.

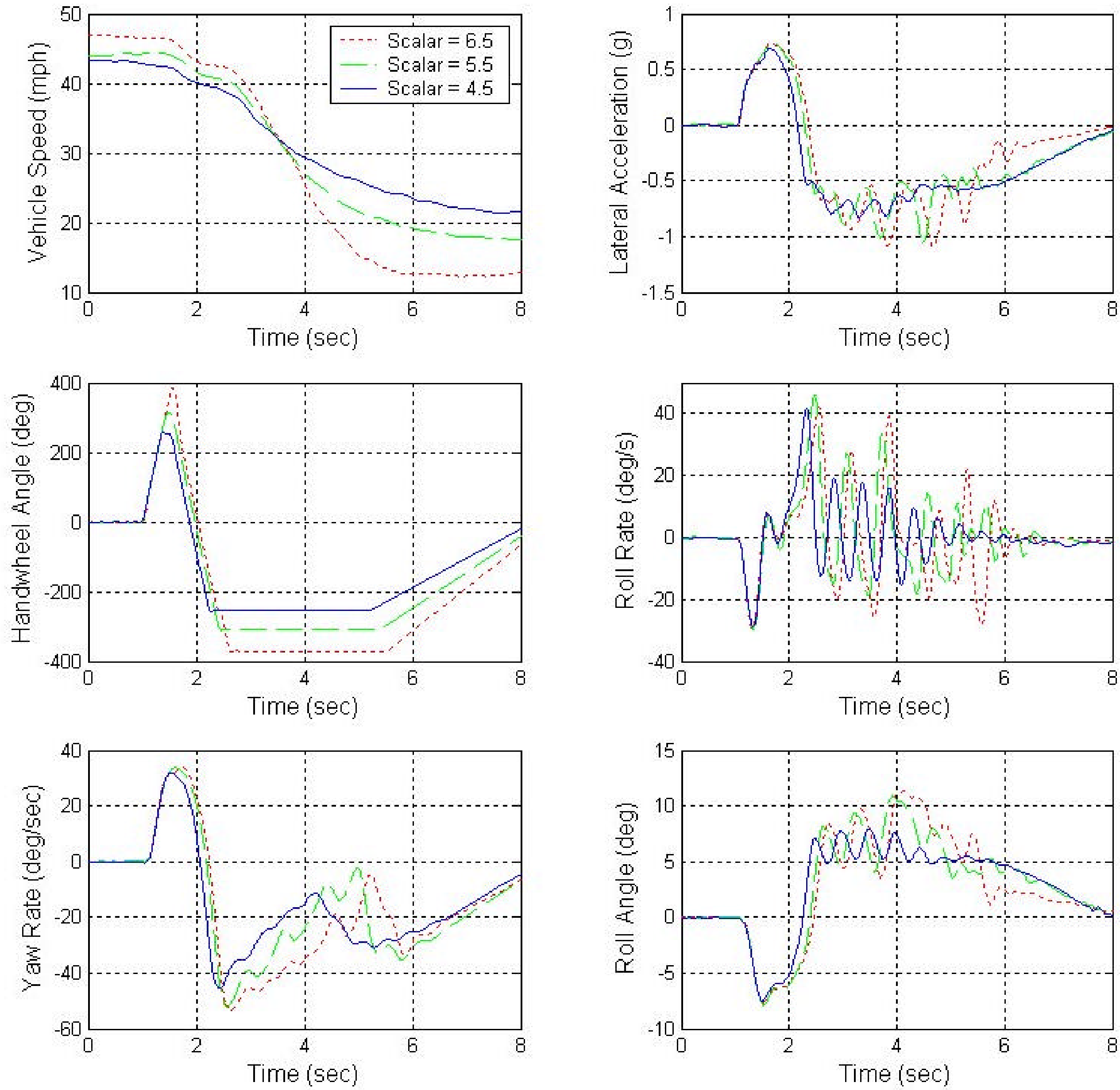

Figure A.12. Right-Left Road Edge Recovery tests performed with a 1993 Ford Aerostar using three steering scalars.

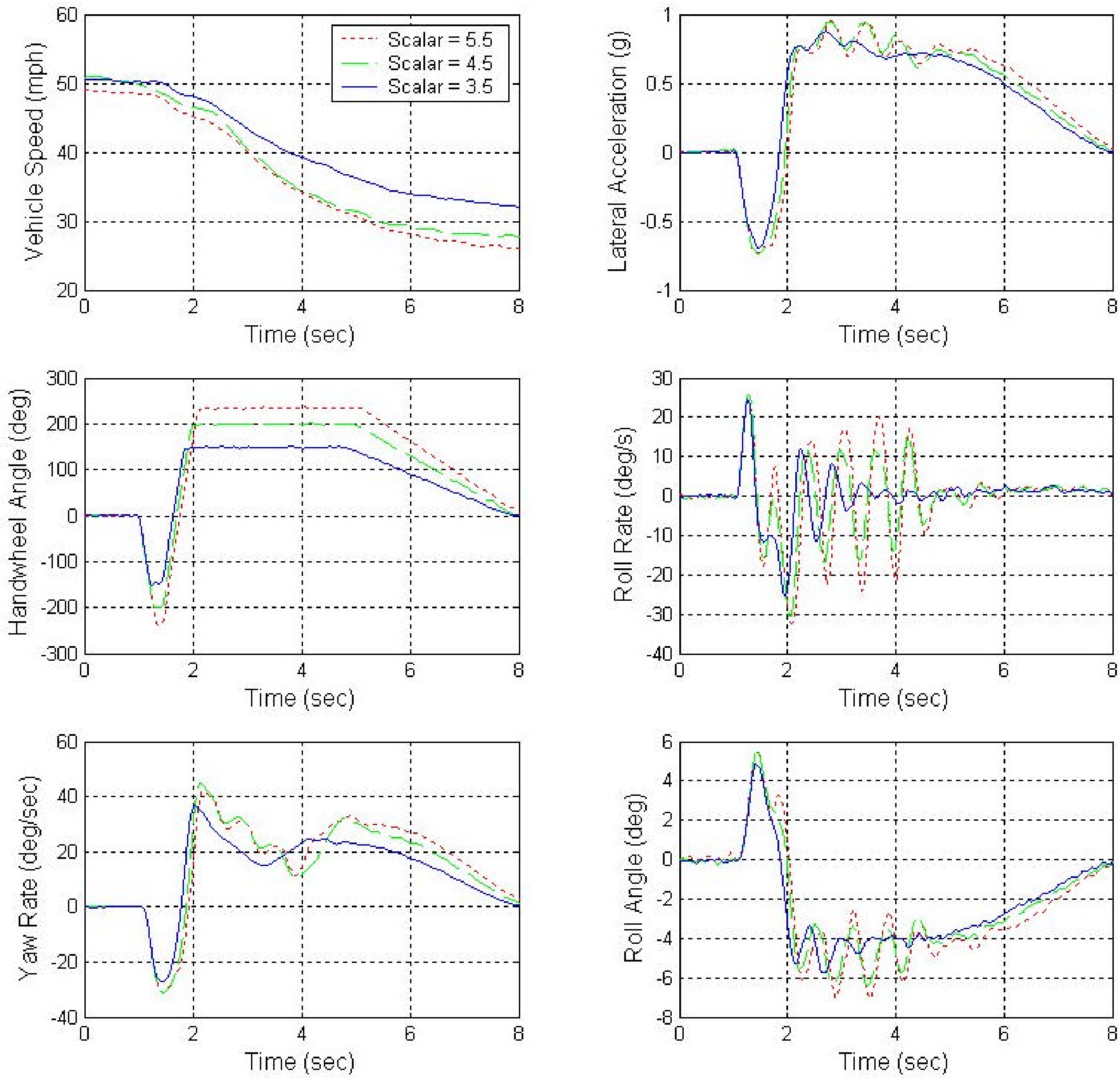

Figure A.13. Left-Right Road Edge Recovery tests performed with a 1997 Ford Ranger 4x2 using three steering scalars.

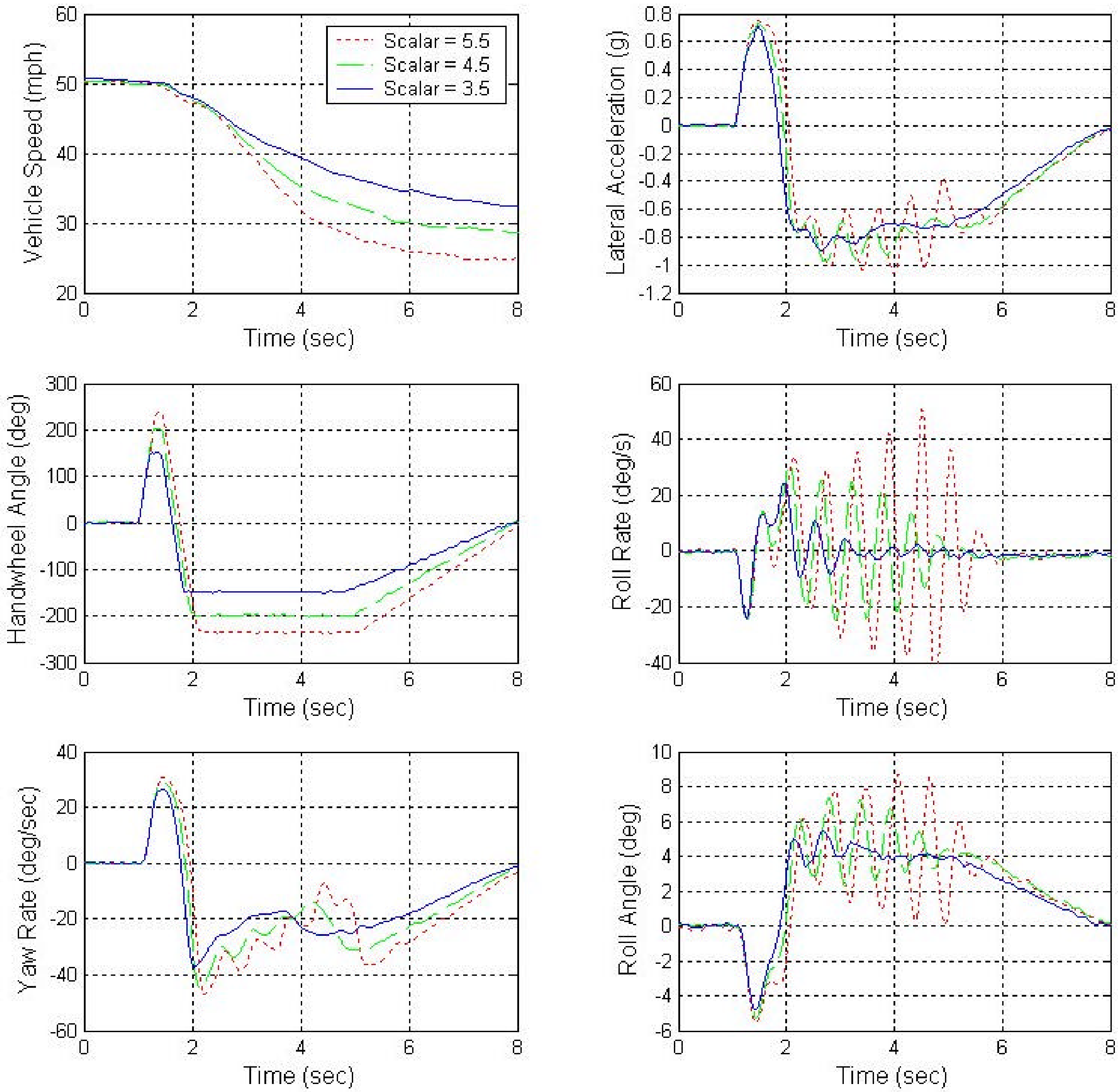

Figure A.14. Right-Left Road Edge Recovery tests performed with a 1997 Ford Ranger 4x2 using three steering scalars.

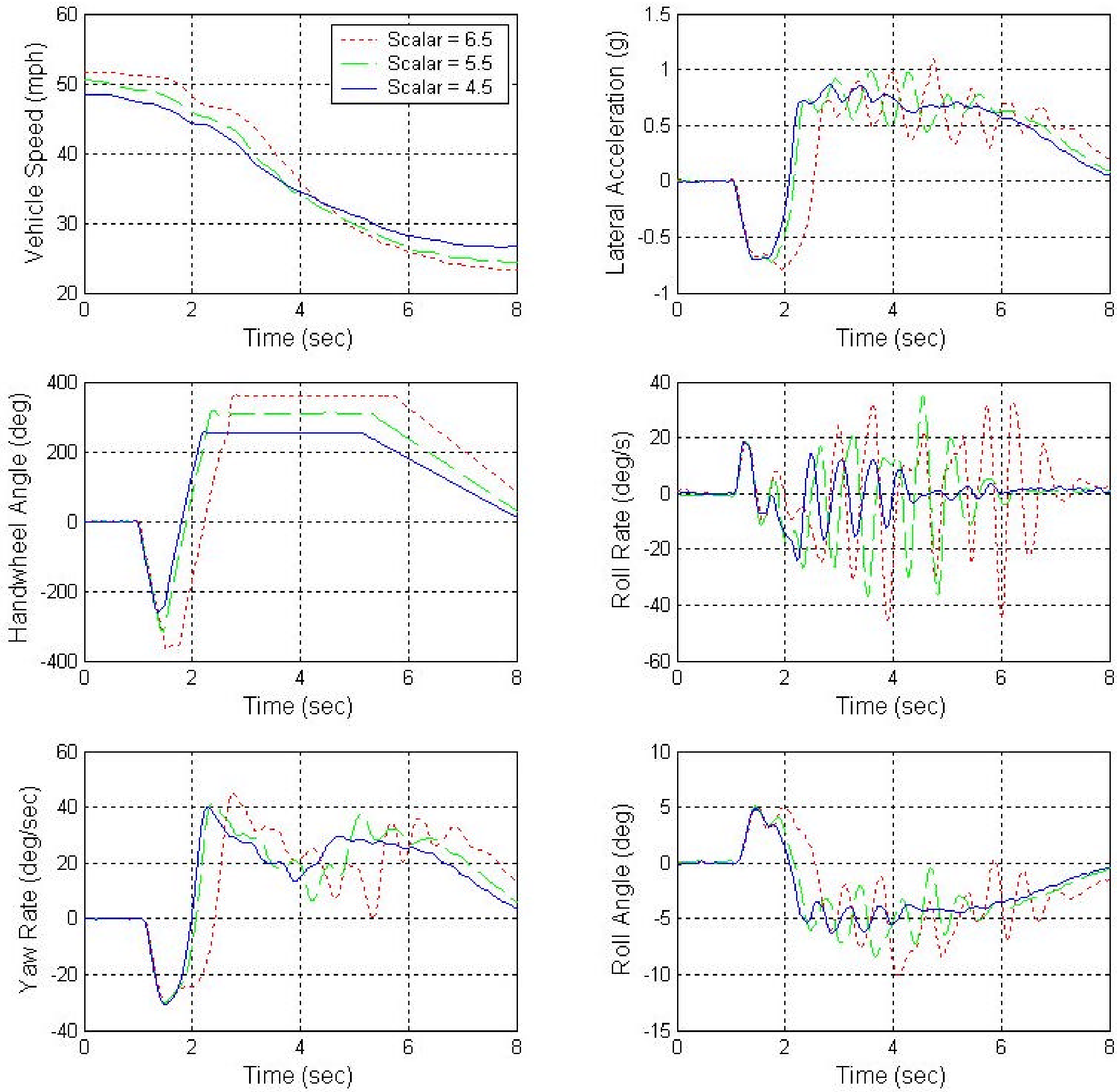

Figure A.15. Left-Right Road Edge Recovery tests performed with a 1997 Ford Ranger 4x4 using three steering scalars.

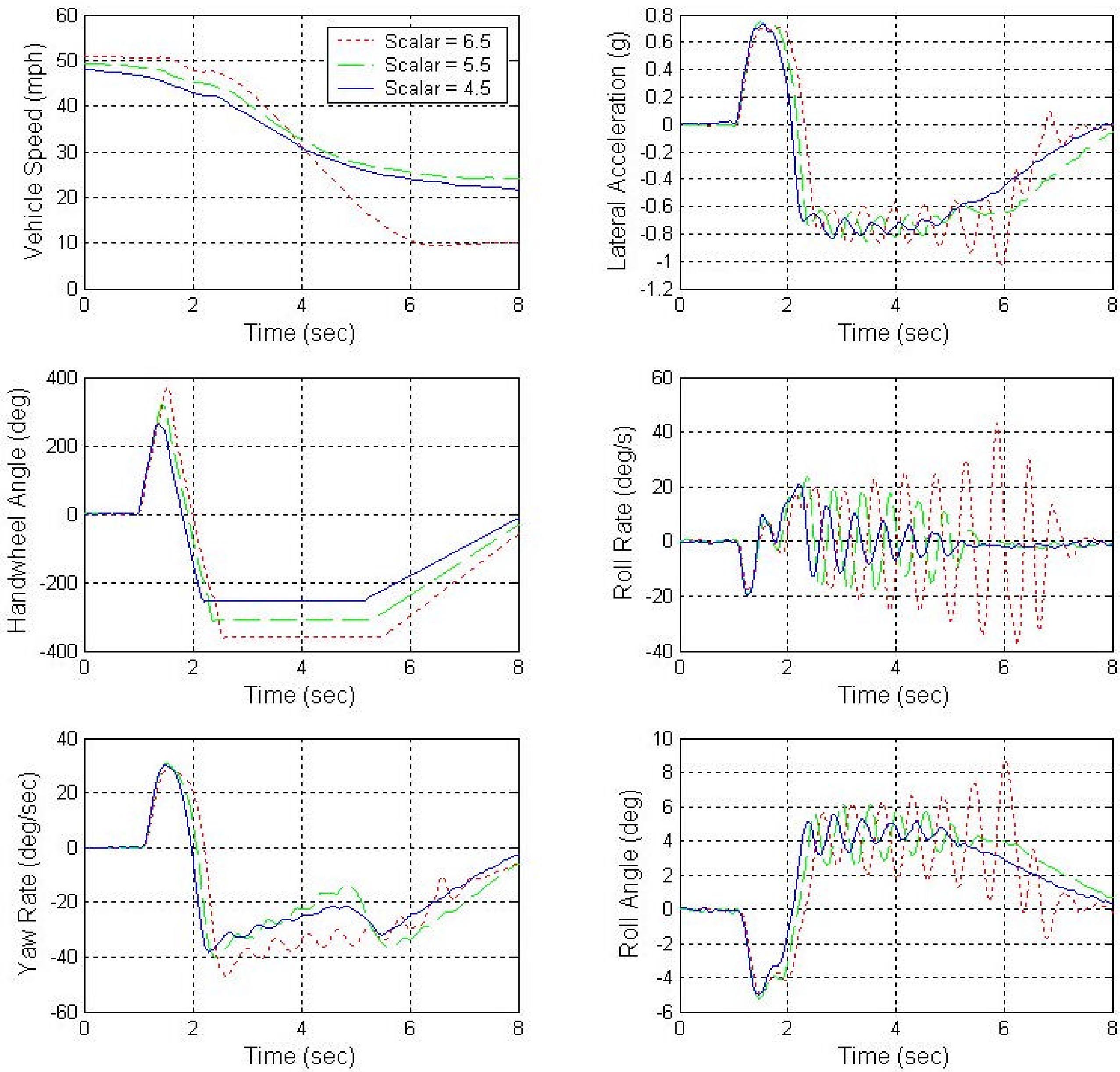

Figure A.16. Right-Left Road Edge Recovery tests performed with a 1997 Ford Ranger 4x4 using three steering scalars.

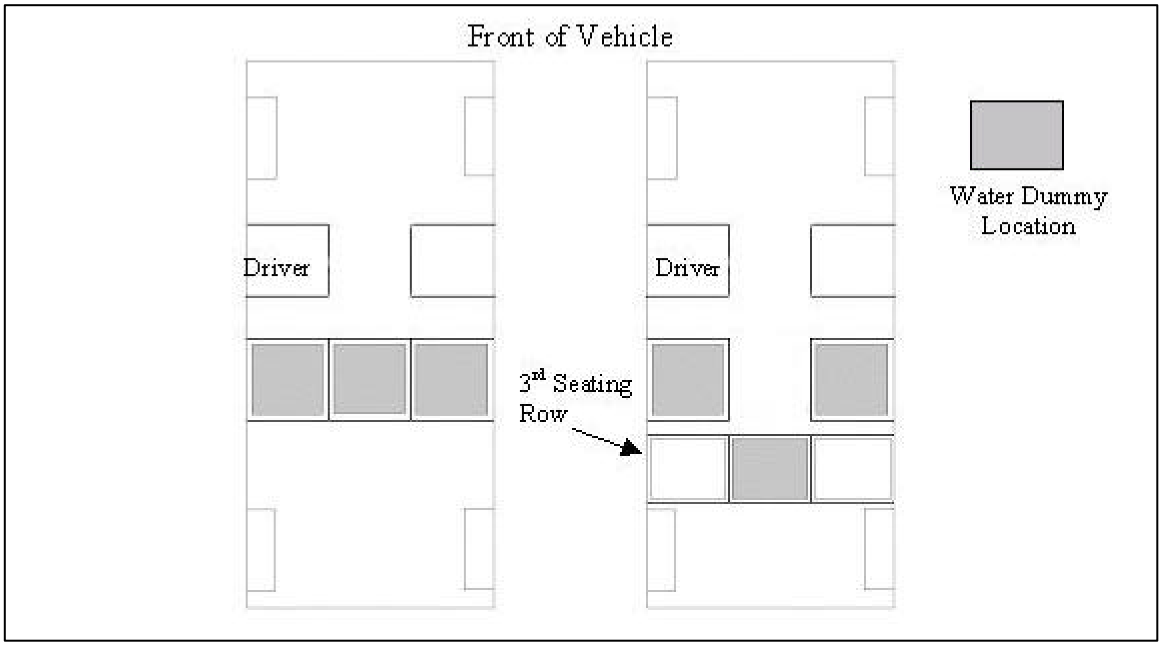

Figure A.17. Water dummy placement for vehicles with three or more designated rear seating positions, excluding pick-up trucks. **Note:** A water dummy is placed in the third seating row only when the second seating row is limited to two designated seating positions.

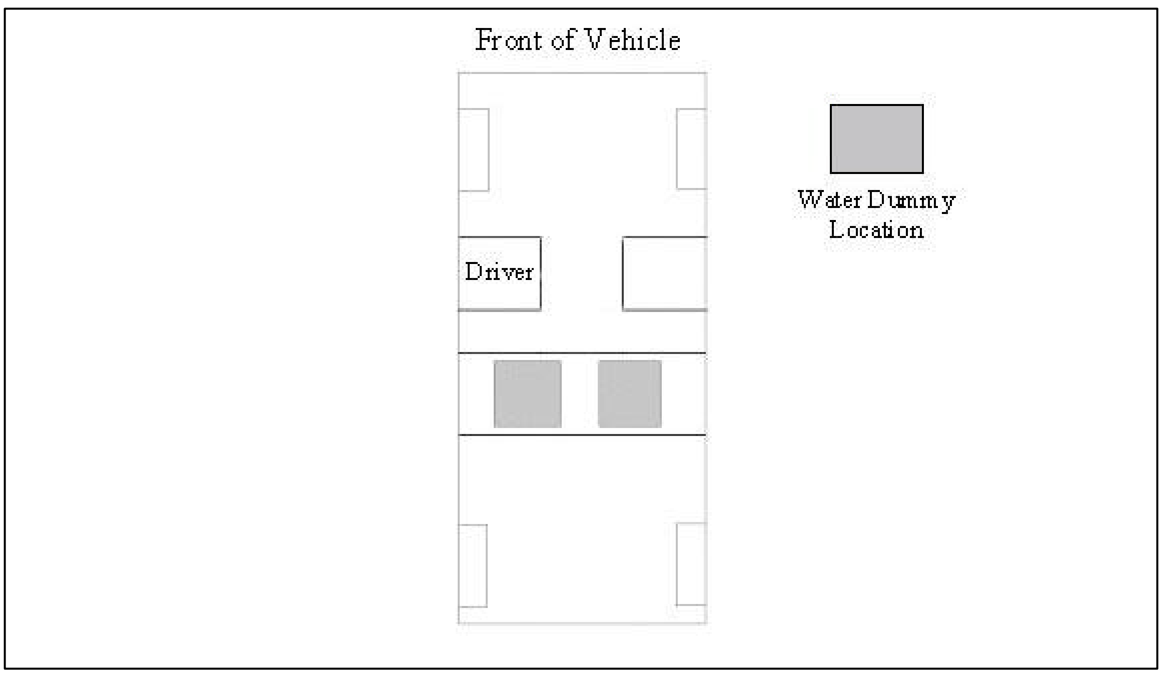

Figure A.18. Water dummy placement for vehicles with two designated rear seating positions, excluding pick-up trucks.

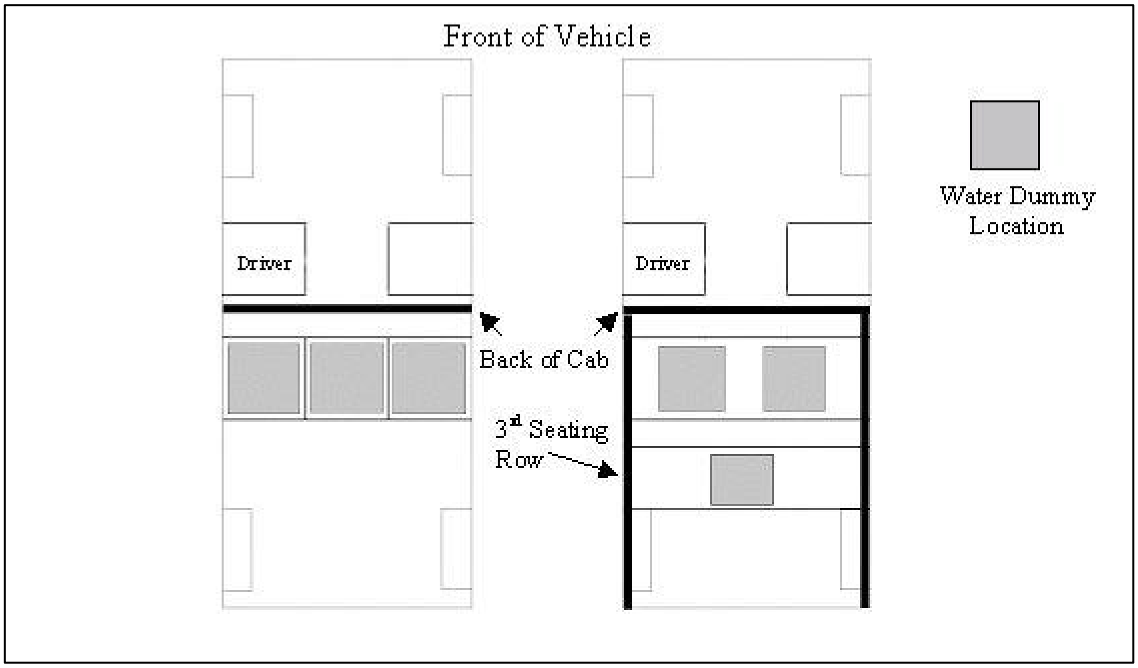

Figure A.19. Water dummy placement for pick-up trucks with no designated rear seating positions. **Note:** A water dummy is placed in a simulated third seating row only when the inside width of the cargo bed prevents the placement of three dummies side by side in the simulated second row.

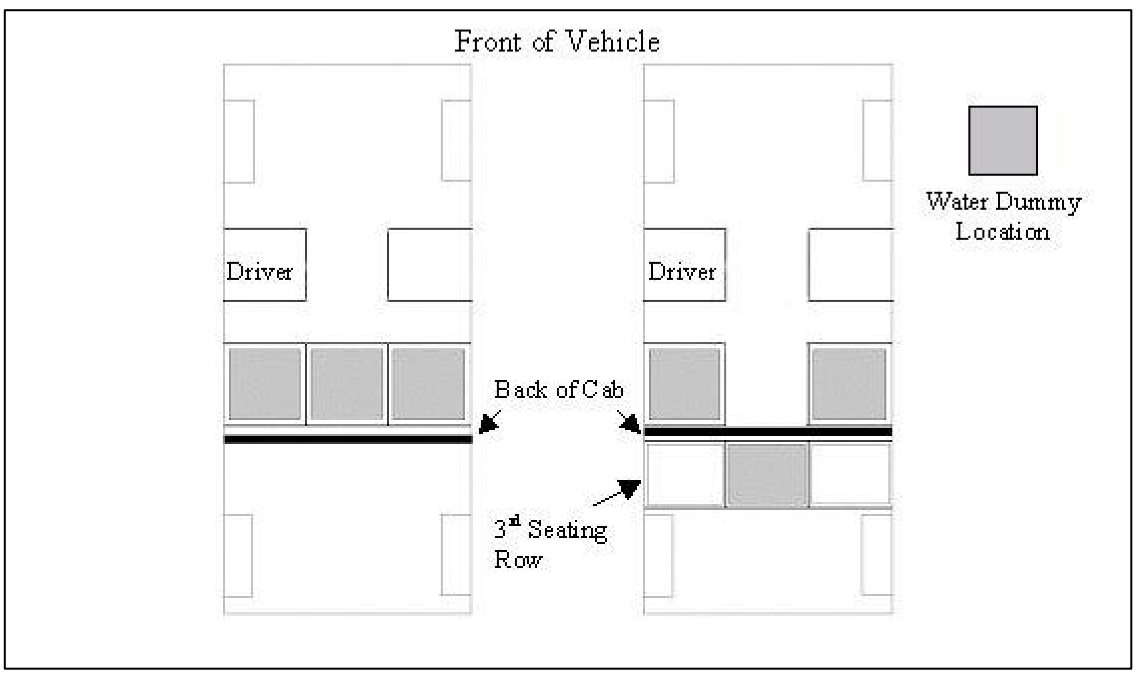

Figure A.20. Water Dummy Placement – pick-up trucks with two or more designated rear seating positions. **Note:** A water dummy is placed in a simulated third seating row only when the second seating row is limited to two designated seating positions.